MINING IN WEAK MUDROCK - VOORSPOED MINE

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Summary

Voorspoed Mine is a conventional truck and shovel open pit operation located north of Kroonstad in the Republic of South Africa. It exploits a single diatreme kimberlite in a host rock consisting of sedimentary strata of carbonaceous mudstones, inter-bedded shale, sandstones and conglomerates with dolerite sills. During the feasibility study site investigation, the country rock geology was felt to be relatively straightforward and the design methodology followed the conventional approach of limit equilibrium stability analysis (checked against empirical analysis) using rockmass converted properties from laboratory testing and core logging. From the very beginning of mining, medium to large scale instabilities caused disruption to production and back analysis of the failures has demonstrated that conventional design is not appropriate for the low strength mudstone units at the site.

The presentation describes how further laboratory characterization focusing on the clay mineralogy in the mudstone identified a clear relationship between unusually weak strata and the smectite content of the unit. It also describes how closer inspection of the core and field mapping indicated trends in bedding orientation, large scale structures and the presence of clay rich seams around the pit that could account for or contribute to a number of possible failure mechanisms. A numerical model that integrates geological complexity and rock strength was used to calculate stable stack angles for the pit that meet corporate risk acceptance criterion. Finally, the risk management systems at Voorspoed and the strategic infrastructure placement are summarized.

1. Introduction

Voorspoed Mine is a conventional truck and shovel open pit operation with a final estimated pit depth of 350m. The mine, located north of Kroonstad in the Republic of South Africa (Figure 1), began production in 2008. It exploits a single diatreme kimberlite dated at 131.8±1.7 Ma (Phillips *et al.*, 1998). During the feasibility study site investigation, the country rock geology was felt to be relatively straightforward and the design methodology followed the conventional approach of limit equilibrium stability analysis (checked against empirical analysis) using rockmass converted properties from laboratory testing and core logging.

From the very beginning of mining, medium to large scale instabilities caused disruption to production and back analysis of the failures has demonstrated that conventional design is not appropriate for the low strength sedimentary units at the site. The following case study describes the geologic, geotechnical and hydrogeologic context of Voorspoed and summarizes the risk management and future design methodology applied to mitigate the adverse consequences of the instabilities.

Figure 1: Location of Voorspoed Mine in South Africa

2. Geological Setting

The following summary of the geologic and structural setting at Voorspoed was obtained from Tect (2013), which references previous work by Stiefenhofer (2003), Mulville (2003), SRK (2004), Rubidge (2005), Selden and Nudds (2011) and Tect (2012).

The country rocks at Voorspoed are predominantly from the Permian period (*c.* 280-200 Ma), and consist primarily of sedimentary rocks of the Volksrust (VO) Formation and the Vryheid (VR) Formation within the Ecca Group and Karoo Supergroup. The VO includes fine-grained, deep-water sediments that are dominated by a massive, but occasionally finely-laminated carbonaceous mudstone. The VR is an aerial and subaerial deltaic deposit that is either a fine grained mudstone (VRM) or inter-bedded shale, sandstones and conglomerates (VRSSC). Depending on whether they can be excavated by conventional shovels or whether they require drilling and blasting, the VO and VR units are qualified as either Rippable or Consolidated. There is also a varved shale (VRVS) unit lower in the sequence. On the property, the VR has been intruded by a number of dolerite sills of variable thickness. Figure 2 illustrates the geologic setting.

The Voorspoed Kimberlite is one of 11 kimberlite pipes found in the Kroonstad area. It consists of one main pipe, made up of eight different Volcaniclastic Kimberlite and Breccia sub-facies but the dominant ones by volume are the Undifferentiated Volcaniclastic Kimberlite (UVK) and Dark Volcaniclastic Kimberlite (DVK). The Kimberlite Country Rock Breccia (KCBX) and the Xenolith rich Kimberlite (XVK) are found along the pipe margins. The Voorspoed pipe is unique in the De Beers Group because there is a very large basalt raft and associated Kimberlite Basalt Breccias (KBBX) that lie against the south east margin of the pipe. The pipe is approximately 12.5 ha at the surface, 6 ha of which are taken up by the basalt raft. Figure 3 shows an isometric view of the pipe and the sub-facies present.

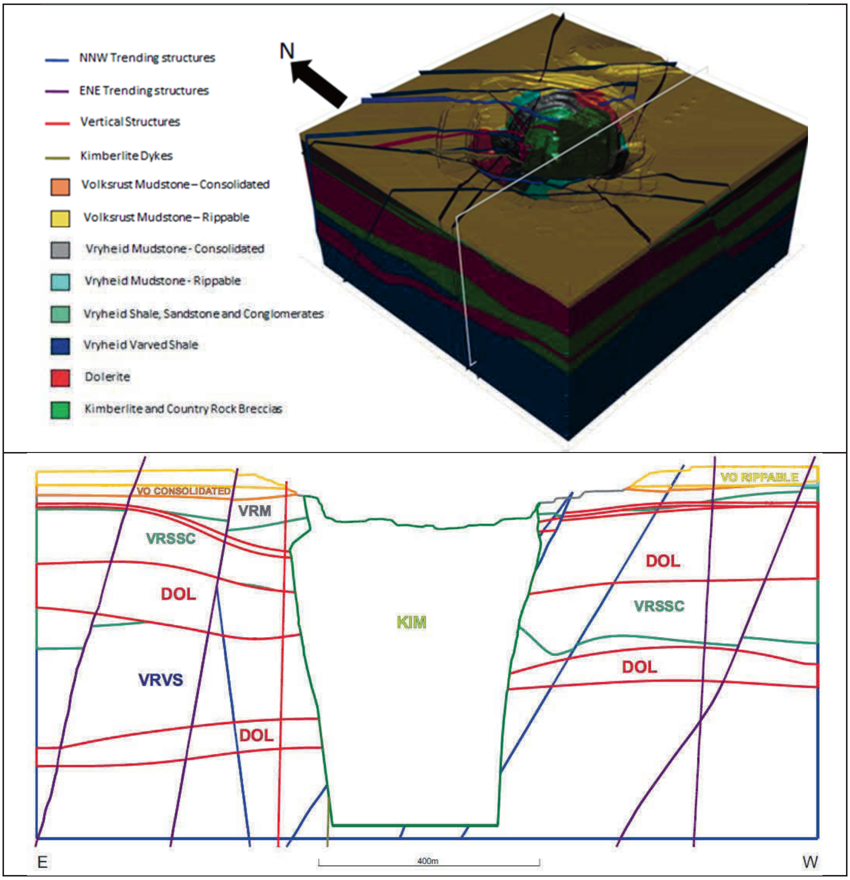

Figure 2: Geologic setting at Voorspoed: Top – Isometric View; Bottom – Cross Section (Tect, 2013)

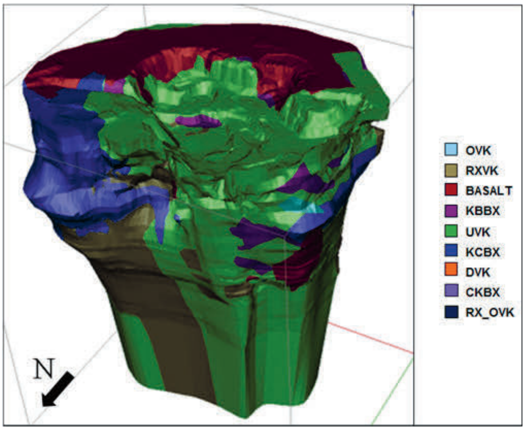

Figure 3: Voorspoed Kimberlite Pipe

Orange River and Kaapvaal Craton dykes trend to the NE and NW respectively on the property (Tect, 2012). The faulting associated with the dykes causes offsetting in the stratigraphy and sometimes play a role in slope instability. Horizontal or shallow dipping bedding is of course present in the sedimentary sequence and flat lying cooling or unloading structures can be observed in the Kimberlite. Figure 2 also shows the fault network.

A halo of disturbed country rock occurs on the periphery of the kimberlite intrusion (Mulville, 2003). This Disturbed Zone is characterized by numerous small, fault- or slump-bounded wedges, which appear to have partially collapsed into the diatreme during its emplacement. This halo plays an important role in slope stability and will be discussed in greater detail later in this case study.

3. Slope Performance

Soon after production began, excessive weathering in the VO unit resulted in loss of bench catchment over most stacks and this was the first indication that mining at Voorspoed might be more challenging than expected. The first large multi-bench failure in the VO occurred in Cut 1 North on 25 July 2009. No instrumentation results were available to help understand the root cause though classical shear failure or a compound type failure was assumed based on observations and back analysis. The photograph in Figure 4 was taken after the first failure.

Figure 4: Photograph of the Frist Stack-Scale Failure in the VO Unit

The design stack angle from the feasibility study was 38° in both the VO and VRM. Target Safety Factors of 1.2 and 1.3 respectively were used for the design. Rockmass properties were first calculated using the GSI approach by Hoek and Brown but were subsequently adjusted based on the engineering judgment of the design consultant (SRK, 2004). The input and assumed properties for the initial Voorspoed slope design are summarized in Table 1 . The slope was assumed dry.

Table 1: Input Properties and Assumed Properties for the Feasibility Study Design (SRK, 2004)

	Input Properties				Analysis Properties	
	UCS (MPa)	m_i	RMR_{L90}	GSI	Cohesion (kPa)	Friction Angle (°)
Basalt	90	15	65	60	150	45
Dolerite	152	50	76	71	150	47
Kimberlite	58	6	66	61	95	39
VO-VRM	16	10	45	40	50	35
VRSSC	37	26	53	48	50	37

Back analysis of the July 2009 failure and two adjacent residual failures resulted in a drop in assumed properties for the VO mudstone. At this point, the VRM was not yet exposed in the pit and observation of the core and review of the laboratory properties suggested it would be more competent than the VO. The design properties and those determined from back analysis are compared in Table 2. The reader is reminded that back analysis requires that the practitioner assume a Safety Factor of 1.0 at failure. It may in fact be lower resulting in a non-conservative determination of properties but this is unknown.

Table 2: Comparison of Design Properties and Properties Determined from Back Analysis (Ruest and Mathibela, 2009)

	Design Properties	Properties from Back Analysis
Cohesion (kPa)	50	36
Friction Angle (°)	35	20

The updated properties and review of slope design resulted in a decrease in stack angle from the original 38° to 26° for a Safety Factor of 1.15 and 22° for a Safety Factor of 1.3. Even with significantly reduced slope angles and a new batter angle of 45° on the bench faces, failures were again experienced in the VO. The photograph in Figure 5 was taken in September 2010. The reader can observe the homogeneity of the VO and very little displacement of the failure into the pit. The consistency of the Rippable VO is "soil-like" near surface. (It is noted that although battered benches proved very effective at mitigating minor sloughing and weathering, the effort required in battering the bench faces resulted in a fifty per cent drop in productivity. In the end, the loss of productivity due to managing the sloughing was outweighed by the loss of productivity due to bench construction. The wider catchment of a conventional vertical bench face mitigated the additional risk by containing much of the sloughing and weathered material. Eventually, the battering was stopped.)

In the following months, a series of failures occurred in both the VO and VR mudstones in Cut 2 on the North-western and South Eastern sections of the pit. The aerial view in Figure 6 shows the location of all of the failures experienced at Voorspoed to date.

Figure 5: Failure in VO - September 2010

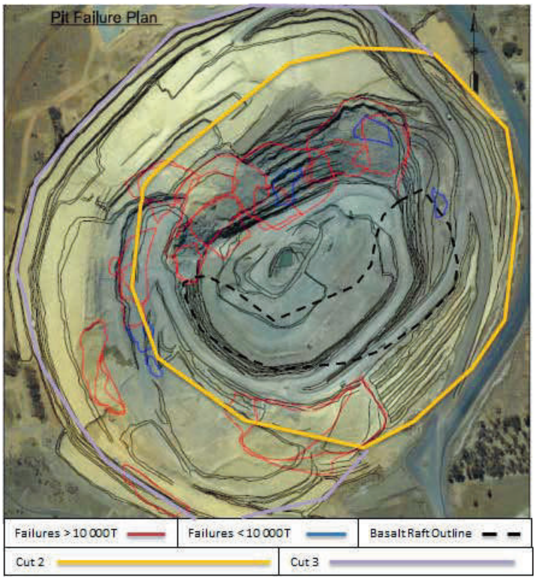

Figure 6: Aerial photo of the pit showing the location of the failures

4. Feasibility Study and Current Geotechnical Domains

The feasibility study geotechnical domains were a function of the lithological units at the site. Slope angles were therefore determined for each of the VO, VRM, VRSSC, Dolerite, Basalt and Kimberlite units. Faults, jointing and bedding orientations were used for kinematic analysis. The stratigraphy was assumed to be shallow dipping with no offsets due to faulting. While a halo of disturbed country rock had been identified during the site investigation, there was insufficient information to delineate its boundaries. Also, other than variation in the bedding dip, inspection of the core did not provide a justification for treating this zone differently in the design. As the country rock was exposed with mining and the need to understand the root cause of the slope failures for future cuts developed, considerable geologic and structural mapping as well as geotechnical drilling were conducted.

A geotechnical model update was undertaken in 2013 that included the following improvements:

- the number and location of major structures;
- the location of a halo of disturbed country rock (as illustrated in Figure 7);
- the presence of a calcite rich layers at the base of the consolidated VRM; and
- the improved understanding of the offset in stratigraphy due to faulting.

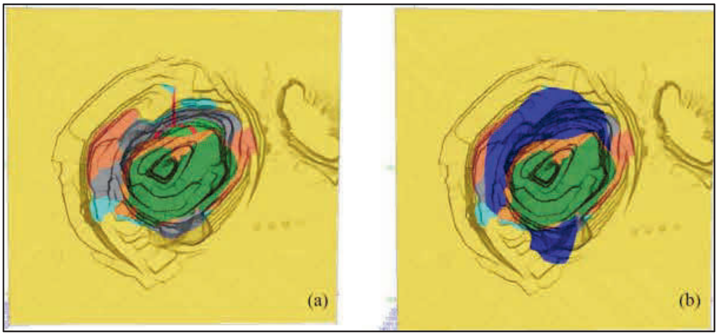

Figure 7: a) Plan view of Voorspoed showing the pit outline overlain by geology; b) Same view as in a) with the Disturbed Zone overlain in dark purple

The regional bedding dip is 10° towards the southwest. However, the halo of disturbed country rock around the pipe consists of several large blocks that were tilted or rotated during the kimberlite emplacement (Tect, 2013). Within these blocks, the bedding can dip either into or away from the pit as steeply as 40°. In order to accurately represent the variation in bedding in the geotechnical block model, the disturbed zone was divided into sub-domains delineated by major structures. Bedding orientation obtained from mapping and core logs was then used to populate the bedding represented within the sub-domains of the model.

5. Laboratory Testing Database and Core Logging Information

A total of 4155 meters of core were drilled and approximately 848 samples for laboratory testing were collected for the Cut 3 slope design resulting in higher confidence in the Voorspoed database (for example, the current database includes 171 mudstone UCS results compared to 14 results from the feasibility study). The updated database summarized in Table 3 provides a good indication of the rockmass characteristics. The intention is to use the 35^{th} percentile values for rock strength (UCS) for design purposes since back analysis of past failures demonstrate that they do not occur at average properties. This will have an impact on the updated slope angles since average UCS values were used during the feasibility study. It is observed in the table that there is a clear drop in rock strength between the top and bottom of the individual stratigraphic units. For example, the UCS values for the rippable portions of the VO and VR units and the top of the VRSSC unit are found to be only 11%, 8% and 22% respectively of the values for the consolidated and bottom portion of these units. In addition, their absolute magnitudes are low compared to what was used in the feasibility study design, these being 16 MPa for the VO and VRM and 37 MPa for the VRSSC. There is also a clear drop in Fracture Frequency, RQD and Density between the top and bottom of the units. While the consequence on the final design remains to be determined, it is clear that there will be repercussions on the recommended slope angles.

Table 3: Laboratory and Logging Data for the Main Lithological Units at Voorspoed

Unit	No of UCS Samples	UCS 35th Percentile	UCS Average	GSI	Fracture Frequency	RQD	Density
VO_RIP	64	2	15	57	4.03	49	2.29
VO_CONS	4	18	17	64	2.62	80	2.36
VRM RIP	3	2	15	21	7.97	48	2.27
VRM_CONS	100	29	36	62	3.68	75	2.47
VRSSC_UPPER	14	26	35	69	1.87	84	2.46
VRSSC_LOWER	68	118	212	73	1.59	82	2.76
VRVS	43	34	61	67	2.81	78	2.77
Basalt	87	60	84	69	0.88	93	2.66
Dolerite	41	301	311	64	1.48	92	2.94

Standard soil testing and X-Ray Diffraction (XRD) analysis were performed on samples from the country rock to determine the clay content and type (Chlorite, Kaolinite, Illite, Smectite). Rock with a high Smectite content weather's easily so careful consideration was given to that mineral. The VO mudstone is of a deep water sediment origin while the VR mudstone is of a deltaic sediment origin. Not surprisingly, all of the VO samples contain some amount of clay and over half contain above 30% clay. However there is some variability in the VO with half the samples indicate less than 20% clay content. Interestingly, the number of samples of high clay content is roughly the same for both the Rippable and Consolidated VO. Smectite is the dominant clay mineral in the VO suggesting greater weatherability in that unit. The Cassagrande Chart in Figure 8 presents the Atterburg Limit tests performed on Voorspoed samples. Most of the samples plotted on the chart are VO and results are as expected for a high clay content but variable soil. Due to the lack of Smectites, the VRM plots much lower for plasticity and the VRSS plots with the silts.

The difference in the clay mineralogy content and type between the VO and VRM is apparent in the moisture content and UCS plots provided in Figure 9 (A-C). The VO unit typically has variable moisture content from low to high reflecting the variability in the Smectite content while the VRM with low Smectite content has lower moisture content. The relationship between moisture content and UCS is typical of rock. While it was initially believed to be a pore pressure effect, many of the high moisture content samples were taken above the water table and so saturation in these would be less than one. The reduction in strength of samples with high moisture content is documented in Romana and Vasarhelyi (2007).

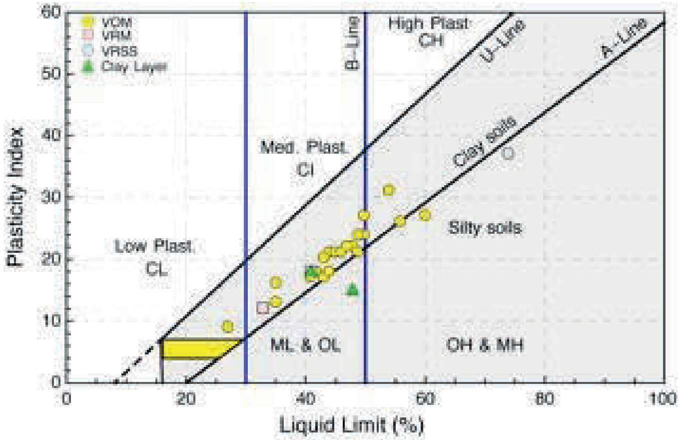

Figure 8: Cassagrande chart of the Voorspoed Atterburg Limit tests

The plots of both moisture content and UCS with depth both reflect the presence of the hydrophylic minerals in the samples tested. It is not unusual to see a drop in moisture content with depth and age of clayey soils. However the plot for the VO, with variable quantities of Smectite, does not clearly show this trend though it is very clear in the VRM. This suggests that the clay mineralogy of the sample is as important as the depth the sample was taken from at Voorspoed. This trend is mirrored in the plot of UCS Vs depth. Again, there is a weak correlation in the VO results but a strong correlation in the VRM results. This again suggest that both the mineralogy and associated moisture content is driving the VO behaviour while only the moisture content is driving it in the VRM. The greater amount of clay minerals in the VRM explains the lower strength compared to the higher strength VRSSC.

In summary, the high clay content in the VO and the relatively high clay content in the VRM are driving the strength and behaviour of those units. The high Smectite content in many of the VO samples is impacting the moisture content and consequently its strength. The variability of the Smectite content around the pit helps explain the time dependency of the failures. There is an observable increase in the VRM strength with depth though it remains a relatively weak unit largely due to the clay content. The VRSSC unit has not been exposed in the pit but these laboratory test results suggest that the low clay content and higher strengths is justification for taking a more classical approach to design in that unit.

6. Precipitation and Groundwater

The average annual precipitation in Kroonstad, 30 km to the south of Voorspoed Mine, is approximately 576 mm while the average annual precipitation is 542 mm at Viljoenskroon, 30 km to the northwest of the mine. Thus, the Voorspoed Mine area is expected to receive approximately 550 mm of precipitation per annum (HCI, 2004). There was no correlation between precipitation events and the failures.

It is noted that the seepage face at the time of the early Cut 2 failures could be observed at approximately 40m below the surface and below the base of the failures providing confidence that the failures were not pore-pressure related. This is consistent with later failures relative to the water table deduced from the piezometers of the 2012-2013 hydro-geologic field study.

A)

B)

C)

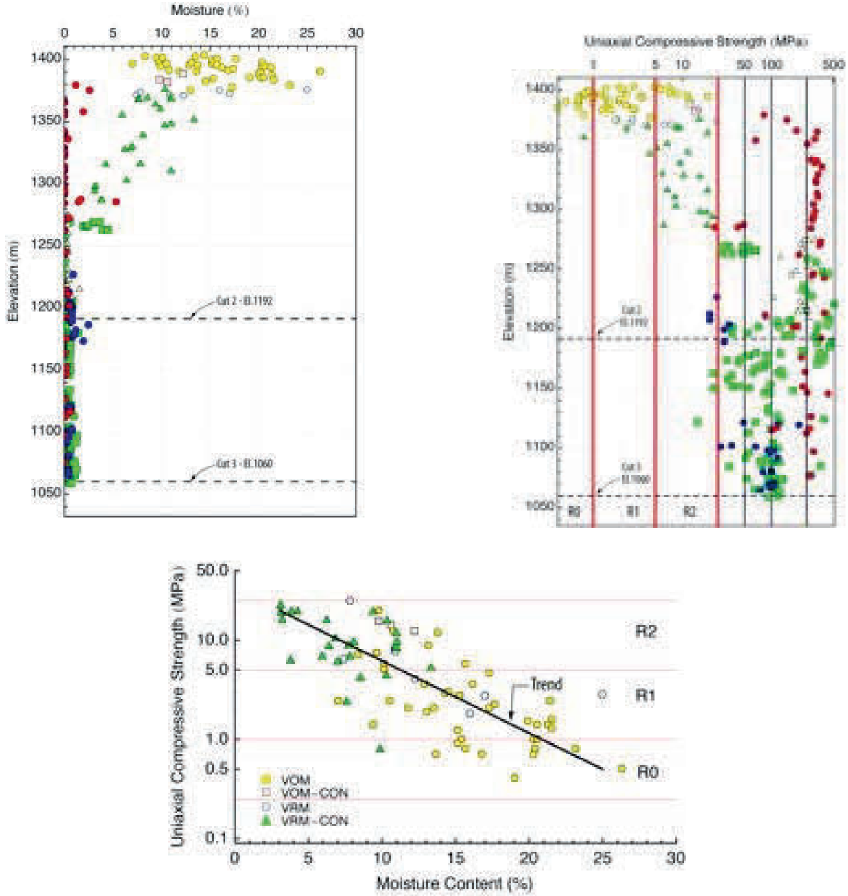

Figure 9: A) Moisture Content Vs Elevation; B) Compressive Strength Vs Elevation; C) Moisture Content Vs Compressive Strength

7. Hypothesized Failure Mechanisms

The Voorspoed geology is more complex than what was originally assumed in the feasibility study design. As the slope failures occurred and additional data and evidence collected, a number of possible root causes were identified. They are discussed in this section.

Classical Rockmass Shear Failure

The photograph in Figure 4 provides a front view of the failure indicating key observations after the failure. The bedding dip in the adjacent mudstone was nearly horizontal and although a portion of the failure broke back to a large scale feature, back analysis of the geometry along with a careful review of the rockmass properties suggested that classical shear failure provided a plausible explanation for the root cause. For safety reasons, the failure was remediated by mining top-down and so the failure surface behind the broken rock could not be observed for visual confirmation.

Classical rockmass shear failure is not expected in competent structure rock where compound failures are more likely. However the Rippable VO is homogeneous and very weak and soil-like behaviour is not unreasonable. At shallow stack angles, the failures initially tend to slump with little run-out. In at least one instance, a failure occurred within the disturbed zone where bedding dipped away from the pit (Tect, 2013). This provides confidence that the failures are not always structurally or bedding related.

Failure on Major Faults

In 2011-2012, after sufficient country rock exposure, the structural geology model was updated through pit mapping and reconciliation with the feasibility study mapping and core logging. The resulting updated structural model is plotted in Figure 10 along with the outlines of the major failures of Cut 1 and Cut 2 at the time of the update. A review of the fault locations relative to the failure outlines indicates that a number of them were bounded by large scale features. Given that many of the large scale features form the boundaries of the Disturbed Zone previously described, it has been hypothesized that some of the failures could be attributed to slip along adverse and steeply dipping bedding within the blocks that appear to have collapsed into the diatreme during its emplacement. However, it is also observed from the figure that a number of the failures are not bounded by the structures or that the structures are not oriented and located to promote failure. It is concluded that major structures might have a role in creating release surfaces at the back for some of the failures but they are not considered to be a primary contributor to the instabilities.

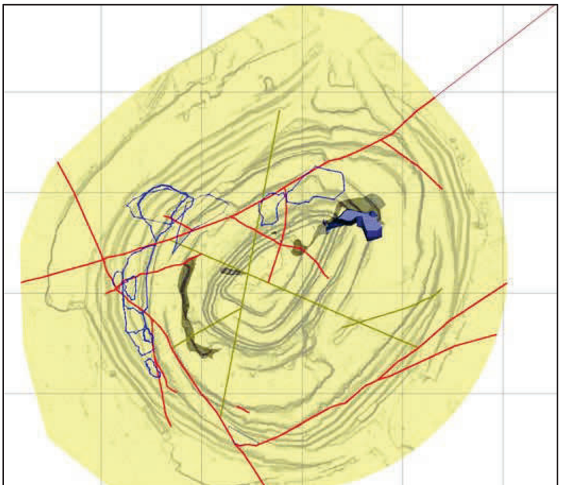

Figure 10: Early structural model and failure outlines plotted on the Cut 2 pit geometry. Major structures are red and the failures up to 2012 are outlined in blue (TECT, 2012)

Basal Failure on Disturbed or Tilted blocks in the Deformed Zone

Some of the failures have occurred on bedding planes and clay horizons of tilted blocks. Their locations correlate with the Disturbed Zone identified during the update of the Geologic and Structural models. Using Sirovision™ data provided by the mine, one prominent weak layer has been interpreted to follow the base of the VRM-Consolidated unit (SRK, 2013). The layer, illustrated in Figure 11 is approximately 5-10cm thick and dips unfavourably into the pit in the North Wall. This failure mechanism has been confirmed by deformation measurements obtained by the mine radars that show outward displacement of the rockmass above the plane and no movement below it. However it is important to note that not all failures have occurred on this layer and consequently, it is considered a risk at the operation but not the root cause of all of the mudstone behaviour.

Figure 11: Calcite/Talc layer interpreted as following the base of the VRM (Consolidated)

Basal Failure on Clay Layers

A likely explanation for many of the failures has been proposed by Martin (2012) and is congruent with the basal failure on tilted blocks mechanism. Martin has hypothesized that *time dependent* and *progressive failure* processes that are common in overconsolidated mudstone, are occurring at Voorspoed. As described by Martin, progressive failure occurs in layered materials exhibiting strain-weakening behaviour. These materials display dramatic strength reduction under small displacement. In mudrocks, the pit excavation induces deformations that concentrate in the softest (weakest) layer in a pit slope and in mudrocks these layers are those with the highest clay contents. The photograph in Figure 12 was taken from Voorspoed core and illustrates how clay layers of some thickness are readily observed in the stratigraphy. The localized strain causes the peak intact strength of the clay beds to rapidly reduce to its residual strength and failure occurs on a basal surface. The failure mechanism is graphically illustrated in the schematic in Figure 13.

Figure 12: Clay seam observed in the Voorspoed core

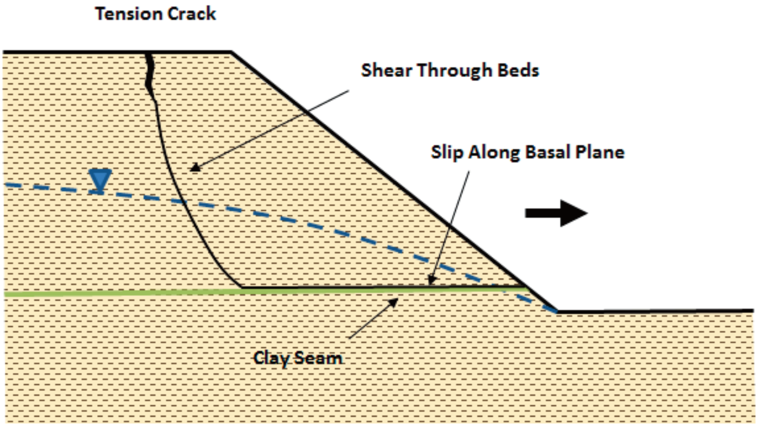

Figure 13: Schematic illustrating basal failure along a clay seam

As the overconsolidated layers in the mudstone are unloaded, groundwater is absorbed in the clays causing them to soften and lose cohesion. This process is normally longer term than the 5-10 day period over which failure occurs at Voorspoed and so this time dependency is likely a secondary process (Martin, 2012). Failures involving planar features are almost always observed only in the Disturbed Zone around the kimberlite ore body.

Summary of Voorspoed Failure Mechanisms and Consequence on Design

The Voorspoed mudstones are clay rich and weak. The VO mudstone has a high Smectite content resulting in increased moisture and an associated further decrease in strength relative to the VR mudstone. Near surface, the weathered or Rippable VO appears homogeneous and relic structures such as bedding, though observable in the rockmass, do not appear to dominate its behaviour. As both the VO and VR become more consolidated, bedding and other larger structures such as jointing and faulting appear to play a more prominent role in slope instability. Although it is tempting to believe that the failure mechanism in the Rippable mudstone is classical shear and the failure mechanism in the Consolidated mudstone is a compound, basal type failure, areas within the Disturbed Zone where bedding dips favourably into the pit wall have also been observe to fail.

For design purposes, numerical models can be used to include both a weak rockmass and bedding that can exhibit the strain softening behaviour described by Martin (2012). The geologic and structural models at Voorspoed now include a Disturbed Zone and they include realistic bedding orientations as determined from mapping and core. The Cut 3 design will be analysed for stability using this advanced model. In the absence of additional laboratory data, some assumptions will be required for the input parameters describing the clay beds. Currently available constitutive laws will not be able to reproduce the time-dependent loss of cohesion due to water absorption suggested by Martin (2012) though a realistic pore pressure distribution obtain by hydro-geologic models will be used in design.

It is the author's opinion, that the VRSSC, Basalt, Dolerite and Kimberite can be treated using the classical GSI approach to rockmass strength.

Although the operation has gone to great lengths to include as much of the available data and current understanding in design as possible, there will be a certain amount of risk management required in future mining at Voorspoed. This is described in greater detail below.

8. Risk Management Strategy

The risk management strategy at Voorspoed consists of an operational component, aimed at managing the current slope instability risks and strategic component which is focused on site investigations and design aspects.

The mine employs a sector based operational risk management philosophy whereby the pit is divided into various sectors and risk is assessed by means of radar/geodetic monitoring, regular pit inspections and a mapping programme. Appropriate controls are defined for each sector and these are captured on a hazard plan that is communicated and distributed to mining personnel on a monthly basis or after every major event.

Monitoring data has demonstrated that instabilities are preceded by several months of creep (1mm per day) followed by increased rates of movement in the weeks before failure (up 20 - 100mm per day). In addition, failures in the mudstones are almost always low-velocity events when compared to typical hard-rock failures. Failure boundaries often migrate over time and can interconnect and join up with other instabilities. Effective slope stability monitoring and the integration thereof into the mine planning and operations are thus essential in such an environment.

9. Future Design and Mining Strategy

The experience at Voorspoed indicates that the VO mudstone fails at stack angles as low as 22°. They are low-velocity events that give ample warning of collapse. Thus the only major impact of the failures on the operation is the loss of access either due to undercutting of the ramp itself or burial of a portion of the ramp and/or production area with failure material.

The mine therefore explored various alternative mining and design strategies with the aim of:

a. Minimizing the impact of failed material on production areas.
b. Mitigating the risk of loss of access.

Minimizing the impact of failed material on production areas

The strategy developed to minimize the impact of a failure was the inclusion of a spill berm in the mine design. The finite difference code *FLAC* (Itasca, 2010) was used to estimate the required spill berm width for a given stack height (Itasca, 2013). Various stack designs were induced to fail in the model and the resulting muckpile displacement was calculated. The spill berm width required to catch 100% of the muckpile was then used for the design.

In order to test the modelled spill berm in practise, a trial mining area was identified in the pit and it was designed at a slope that was steep enough to ensure failure. The South western quadrant of the pit was selected for this purpose and it was mined under controlled conditions at a maximum stack angle of 38°, at a stack height of 36m and with a 20m spill berm width as illustrated in Figure 14.

The stack failed as predicted and the initial spill width was less than 10m - well within the 20m design spill berm width. However based on previous Voorspoed experience, saturation of the muckpile after major rainfall events causes the run-out to extend as much as 50% beyond the initial failure base. The 20m design width was therefore deemed sufficient and has become the standard for the operation.

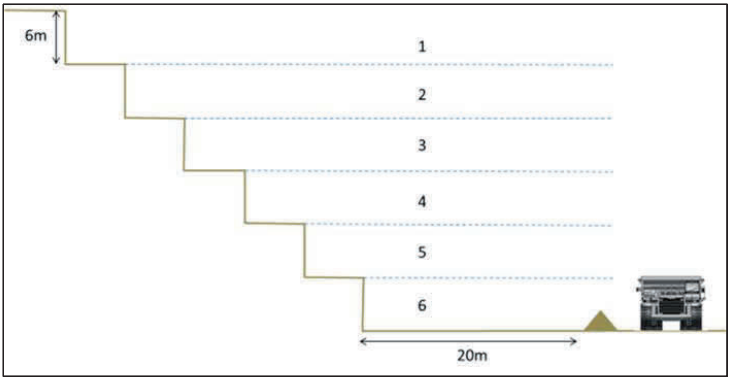

Figure 14: The trial mining sequence. A 36m stack, consisting of 6m high benches, is conventionally developed (mined sequentially) and a 20m berm left at the bottom of the stack. The slope was then left to fail.

Mitigating the risk of loss of access

The mine initially started off with a conventional concentric pit design, which eventually evolved into a split shell design. Unfortunately, in both designs substantial portions of the ramp system were placed in the VO and VR mudstones. This resulted in the loss of two of the three ramp systems during the early stages of mining. The initial remedial and recovery attempts consisted of backfilling and compacting the failed sections and proved to be unsuccessful. The only way to ensure ramp stability is to place as much of it within competent units and to buttress the portions of the ramp exposed to the mudstones as in Figure 15. Buttresses of this size take up a significant amount of space and take time and resources to construct and are not an ideal remediation solution for efficient production.

To date no major multi-bench failures have occurred in either the Basalt or Kimberlite units. These are however characterised by intermittent local rockfalls, during major rainfall events, in locations where bench retention has been compromised.

Figure 15: Buttress below the North Ramp. Photo taken in December 2012.

The lessons learnt from the initial challenges with ramp stability were incorporated into the design of the next cut with all of the ramps placed in the competent lithological units (Basalt raft, Dolerite sills, Kimberlite and VRSSC Lower). See Figure 16

The operation has been mining an intermediary Cut 3 design for almost 2 years now, with the current mining horizon 42m below ground surface. The only major failures to date in this mining cut were in the Trial Mining Area previously described. The fact that the mining methodology in Cut 3 is different from Cut 2 (conventional stability design vs. induced failure) makes the direct correlation of slope performance in the various cuts difficult.

10. Conclusions

The recent site investigation programme coupled with extensive empirical experience and back analysis of slope performance significantly contributed to the understanding of the failure mechanisms, risk management and mining strategy in a weak rock environment.

The Voorspoed mudstones are clay-rich but there is a significant difference in the character of the VO and VR units. The VO has variable amounts of Smectite that appears to dominate its moisture and associated strength characteristics. The VR mudstone has very little Smectite and appears to be more competent and displays more classical characteristics of strength and moisture content with depth in clay rich rock.

The behaviour of both the VO and VR mudstones is dominated by the rockmass strength and where it is weak and homogeneous, classical shear failure is observed. Where the rockmass is of better quality, the behaviour is dominated by the presence of clay rich beds and other unfavourably oriented structures. The design will account for this multi-mechanism behaviour by ensuring that rockmass strength is accurately represented in analyses using calibrated properties and that bedding orientation and strength is accurately represented in the geologic/structural model.

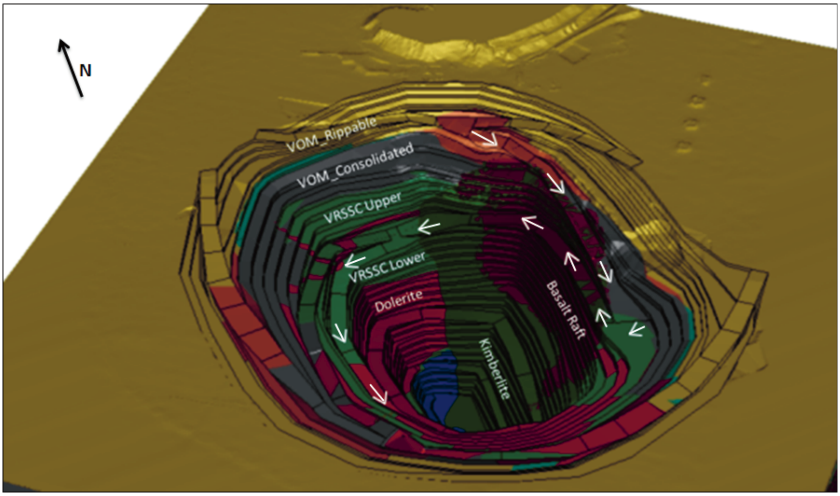

Figure 16: Isometric view showing the new planned ramps system in Cut 3 on the west in competent ground: Basalt, Kimberlite, Lower VRSSC and Dolerite Sills.

Considerable amount of time and resources have been invested in order to understand the characteristics of the Voorspoed geology. However, there will always be some uncertainty in the slope performance that must be handled using an appropriate risk management strategy. The previous strategy was aimed at restricting the probability of slope failures to within conventional slope design criteria. However a policy of accepting and designing the slope to fail under controlled and monitored conditions has proven to be very effective for efficient mining of the mudstone. Buttressing local instabilities below ramp systems and battering benches to mitigate against sloughing are also highly effective measures however the economics of these strategies will determine their viability for specific operations. The most effective risk management strategy at Voorspoed is to manage planned failures within spill berms and develop the ramps within the more competent and stable units at the site.

References

HCI (2004). *Predicted Ground-Water Conditions at Proposed Voorspoed Mine Based on Preliminary Ground-Water Flow Modelling*. Report to De Beers Consolidated Mines. August 2014

Itasca (2013). *Predicted Groundwater Conditions at Voorspoed Mine, Prepared for De Beers Consolidated Mines*. By Lui. H.

Martin, D. (2012) *Personal Communication*. October 2012

Mathibela, K., Ruest, M. *Note for the Record – Voorspoed Slope Design for VO and VRM Mudstone*. Internal Report to Voorspoed Mine. January 2011

Morkel (2011) *Venetia Weathering Study*. Report Number: Vws R04 Final Report

Mulville, D. (2003). *Geotechnical Site Investigation for Voorspoed Diamond Mine*. Mulville and Associates, Report no 20219, prepared for De Beers Consolidated Mines.

Phillips, D., Machin, K.J., Kiviets, G.B., Fourie, L.F., Roberts, M.A. and Skinner, E.M.W. (1998). *A petrographic and 40Ar-39Ar geochronological study of the Voorspoed kimberlite, South Africa: Implications for the origin of Group II kimberlite magmatism*. South African Journal of Geology, 101 (4), 299-306.

Romana and Vasarhelyi (2007). *A Discussion on the Decrease of Unconfined Compressive Strength Between Saturated and Dry Rock Samples*. 11th ISRM Congress, Lisbon, Portugal, July 2007

Rubidge, B.S. (2005). *Re-uniting lost continents – Fossil reptiles from the ancient Karoo and their wanderlust*. South African Journal of Geology, 108 (1), 135-172.

Rubidge, B.S. (2012) *Assessment of the Sedimentological environment at Voorspoed Mine*, University of the Witwatersrand, Report to Voorspoed Mine

Selden, P. and Nudds, J. (2011). *Karoo Evolution of Fossil Ecosystems (2nd Ed.).* Manson Publishing. pp. 104-122.

Steffen, Robertson and Kirsten (SRK) (2004). *Geotechnical Evaluation and Slope Design for the 200 m Pit Feasibility and 400 m Pit Pre-Feasibility Study, Voorspoed Mine*. Steffen, Robertson and Kirsten (SRK) Report No 3348385.

Steffen, Robertson and Kirsten (2013) *Voorspoed Mine Geotechnical Model, Report Prepared for Voorspoed Mine*, De Beers Consolidated Mines. SRK Consulting (Canada) Inc. 2CD002.022. December 2013. By Barnett. W.

Stiefenhofer, J. (2003). *The Geology of the Voorspoed kimberlite and surrounding country rock*. Report from the Mineral Resource Management unit of De Beers Consolidated Mines.

Tect Geological Consulting (2012). *Review and 3D Modelling of Country Rocks and Major Structures, Voorspoed Mine*. Unpublished report prepared for De Beers, 10/07/2012. By Basson. I.

Tect Geological Consulting (2013). *Review and 3D Modelling of Country Rocks and Major Structures, Voorspoed Mine 2013 Update*. Unpublished report prepared for De Beers, 21/06/2013. By Basson I.