KEY GEOTECHNICAL CHARACTERISATION PARAMETERS FOR TRANSITION MATERIALS IN DEEP WEATHERED DEPOSITS AND THEIR INFLUENCE ON BENCH SLOPE STABILITY.

Edward Saunders,
Senior Rock Mechanics Consultant, SRK Consulting Ltd.

The bench slope performance of transition zone materials in deeply weathered deposits are highly variable due to the inherent soil and rock masses complexity, and the excavation practices that are utilized to form these slopes. For the most part, the transition materials are difficult to characterise due to their geologic variability and preferential weathering processes. Additionally, the early characterisation of these materials is often carried through to the slope design and implementation.

This paper presents an evaluation of the geotechnical parameters that are used to characterize the transition zone materials at the study phase and then refined during pit exposure. Geotechnical characterisation and bench slope performance aspects have been detailed using case study examples from operating mines. In addition, the controlling factors on transition bench slope performance has been reviewed and back-analysed using bench-break break probabilistic techniques.

1. INTRODUCTION

This paper reviews the characterization and bench slope performance of transition rock materials that are excavated within deeply weathered deposits. Often the transition is difficult to characterize due to preferential weathering processes and the inherent material geologic variability which can be governed by soil, rock and discontinuity strength criterions.

Consequently, open pit slopes may be over conservative or aggressive in design due to characterisation limitations. This can included more simplistically the extent and elevation of transition contacts or the governing strength criterions which are difficult to determine. Additionally, operational challenges such as excessive blast energies can further disrupt a weaker transition and result in adverse stability performance including significant heave, over-break and rock fall.

Deeply Weathered Rock Profile

The soil and rock profile is derived from the in-situ weathering and decomposition of the bedrock by physical and chemical processes (Stacey & Martin, 2013). The terminology for the weathered rock profile differs across publications and the engineers responsible for slope design. The typical four units of the weathered profile are geologically described below:

- **Residual Soil:** Soil material where the mass structure and fabric of the protolith bedrock are completely disintegrated. The soil can exhibits significant changes in volume and minerology, and has not been significantly transported (Fookes et al, 1997).
- **Saprolite:** Completely to highly weathered zone in the soil strength range. The saprolite matrix is supported by soil materials and may contain bands of more resistant rock and relic structures.
- **Transition:** Highly to moderately weathered materials typically in the very weak to weak rock strength range with well defined rock structure located between the saprolite and fresh rock. The transition may contain soil materials. The underlying contact with the Fresh Bedrock is typically sharp.
- **Fresh Bedrock**: Slightly weathered to fresh rock with no significant discolouration and may show localised iron staining along discontinuities where water flow is observed (Abrahams, 2013).
  The units have been intentionally described using a geological terminology, as the actual geotechnical characterization can be site specific, and the parameter assignment based on those collected during field investigations and/or from exposed bench slopes. Figure 1 shows a schematic of the typical deeply weathered profile and Figure 2 shows the general appearance across a pit slope at the Rosebel Mine, Suriname.

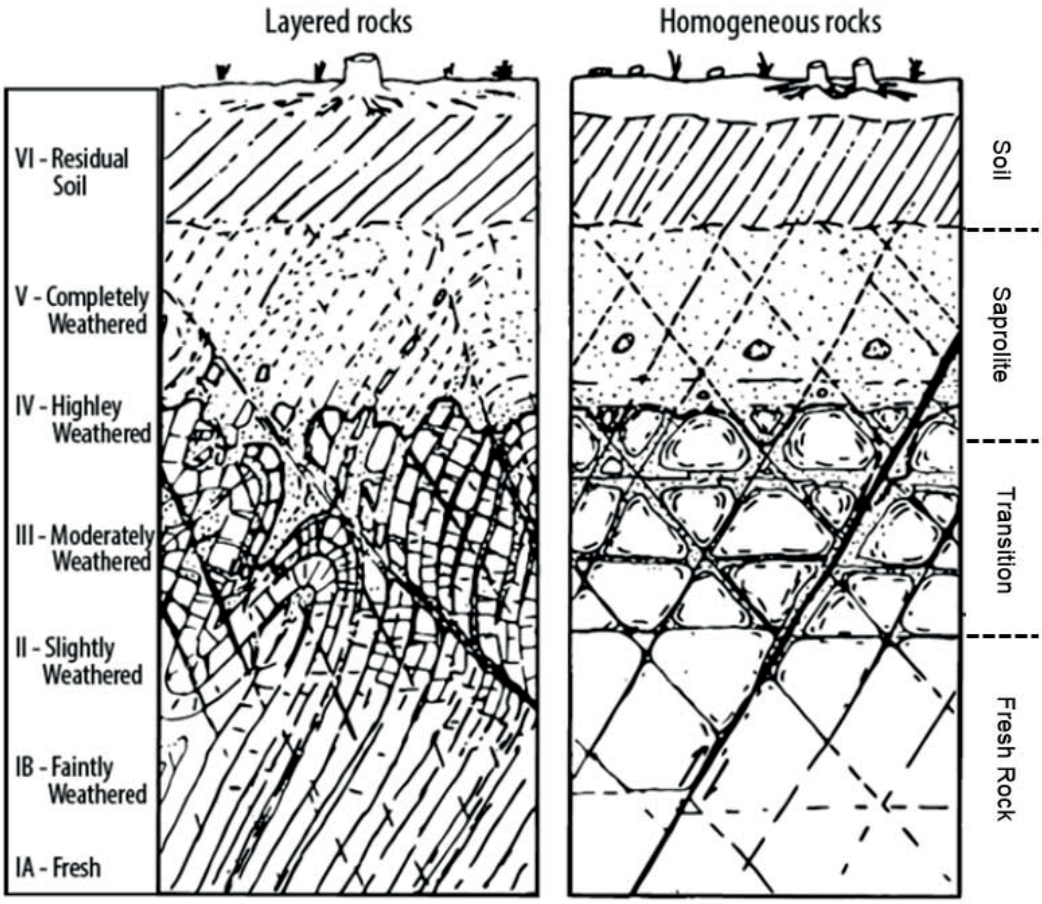

Figure 1: Generalized deeply weathered rock profile (modified from Deere and Pattern, 1971 and Stacey and Martin, 2013)

Figure 2: Weathered Rock Profile Exposed Through Bench Slopes at the **Rosebel Mine, Suriname**

Discussion on Transition Rock Mass Strength

The transition materials often exhibits intact rock strength across most ISRM ranges. This can make it difficult to characterize strength reliably by either soil mechanics or rock mechanics methods (Major, 2009). The overlying saprolite may also exhibit variability, however, more commonly the strength of these materials are primarily controlled by matrix soil mass and/or poorly defined relic structures, both of which can be determined using a mohr-columb criterion approach.

The transition typically comprises weak intact rock which is on the lower quality scale using rock mass rating systems. A gradual change from soil mass or weak rock mass strength toward a governing inter-block shear failure strength generally exists as increasing intact rock strength is observed (Castro et al, 2013). Transition rock discontinuities are more typical weathered and/or infilled, lowering the inter-block frictional shear strength properties which can govern kinematic stability. Kinematic instabilities observed within the transition may not be observed in the equivalent fresh rock, such as the well-defined toppling shown in Figure 3.

The weathering profile can be irregular or exhibit localised depressions which can drive strength variability across a single bench elevation. Furthermore based on experience, where the overall mass comprises a proportion of weaker material greater than about 25%, the weaker portion can govern the overall strength (and stability) of the slope.

Other factors such as excessive blast energies can dilate discontinuities within in already weak rock mass, further reducing the inter-block strength. The development of compression or extension cracking during blasts can also fracture the intact rock pieces, reducing overall rock mass strength. Figure 4 shows dilation along bedding and cross-joints related to heave of the rock from an irregular shaped and larger trim blast.

Figure 3: Toppling Instability related to well defined rock structure exhibiting lower friction strengths.

Figure 4: Transition Rock Materials exposed across a recently blasted Bench Slope

2. GEOTECHNICAL CHARACTERIZATION

It is important to understand that the initial characterization of deeply weathered materials is typically completed using the results the exploration drilling. Geological descriptions, such as the weathering classification, are key to the conceptual and preliminary characterization (or model). Subsequently, these models may be carried through the slope design, the implementation in the pit and even used for ore processing. Figure 4 shows a generalized flow-chart summarising the geotechnical characterization process. The *geotechnical model* incorporates geological, structural geology, rock mass and hydrogeological components.

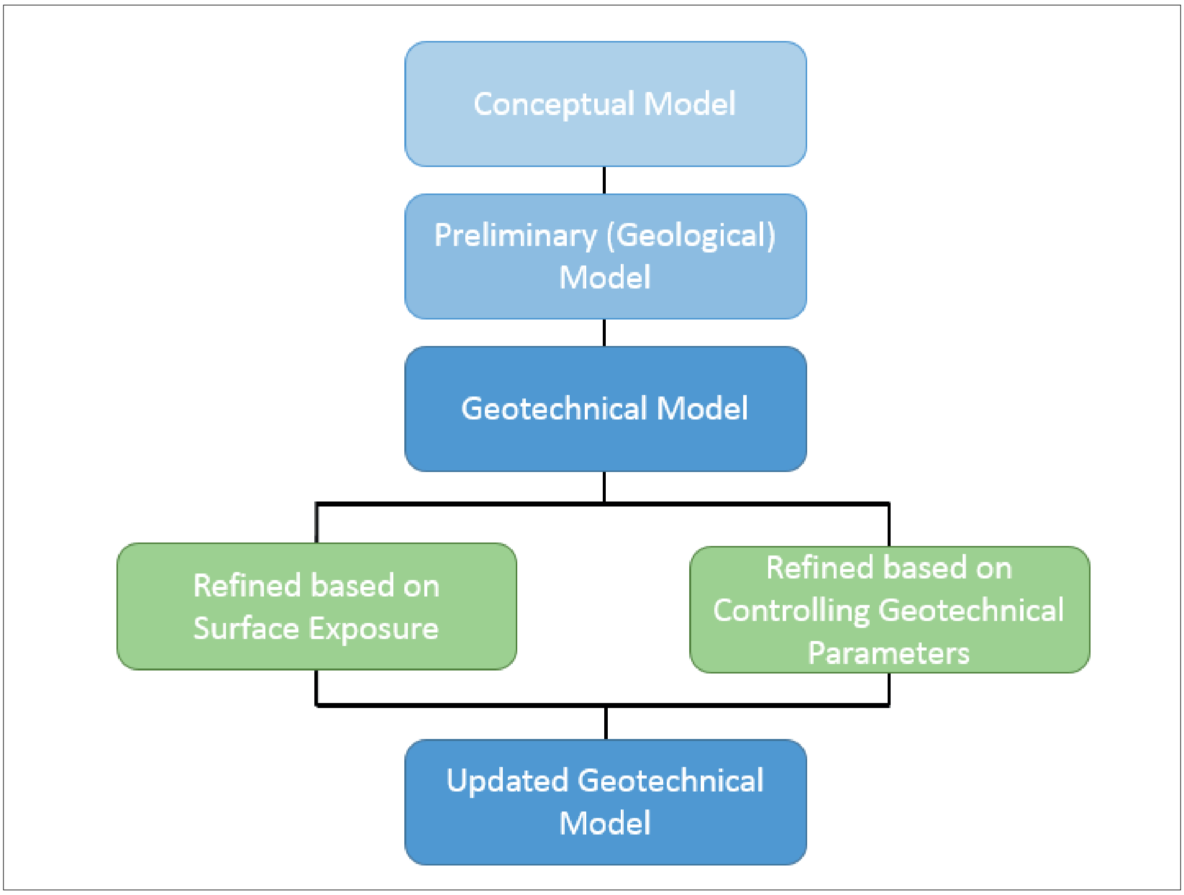

Figure 4: Geotechnical Characterization Flow Chart

3. CONCEPTUAL AND PRELIMINARY (GEOLOGICAL) MODEL

Development of a conceptual model is based on the expected geology and deposit mineralization context. Anticipated rock types and weathering profiles are based on available information and experience with similar deposits. Such conceptual models are discussed in the Total Geological Approach paper authored by Fookes et al (1997).

The preliminary characterization of the weathered rock profile occurs at the exploration phase. The results of the exploration logging, including geological and weathering descriptions, often delineate the contacts between each unit. This initial characterization may also be supported with basic mechanical logging data such as Total Core Recovery (TCR) or Rock Quality Designation (RQD).

4. GEOTECHNICAL MODEL

The actual weathered rock profile exposed can significantly differ to that defined in preliminary models. The soil and rock between the exploration drillholes maybe poorly defined and/or discrete geological structures may not have been intercepted. To develop a geotechnical model, the results of the dedicated drilling and characterization work should be conducted. Multiple geotechnical logging and laboratory testing parameters should be evaluated, including:

- RQD;
- Fracture frequency;
- Estimated ISRM field strength;
- Laboratory rock strength testing;
- Joint condition ratings (RMR_{76}/RMR_{89});
- Geological Strength Index (GSI);
- Rock Mass Rating Systems (RMR_{76}/ RMR_{89});
- Qualitative rock quality estimates from exploration core photography; and
- Hydraulic conductivity properties.

Figure 5 shows a comparison of selected geotechnical parameters from drillholes intercepting a pit wall through a deeply weathered profiles. Using Leapfrog Geo 3D software, Figure 5 shows the variability in the geotechnical parameters as expected for a rock in the *very poor* to *good* rock quality RMR range. (Bieniawski, 1989).

5. REVIEW OF SITE-SPECIFIC GEOTECHNICAL PARAMETERS

Site specific geotechnical logging, laboratory rock strength testing and hydraulic testing parameters have been compiled and evaluated against the deeply weathered profile. This review is based on initial work by Blight (2012). The parameters have been collected from investigations at operating mines, including IAMGOLD's Essakane (Essakane and Falagountou Pits) and Rosebel (Rosebel and J-Zone Pits) mines, and operating mines located in Guyana and northeast Brazil. The following observations specific to the transition can be made:

- A sharp RQD (%) increase is observed at the saprolite and transition contact as rock structure becomes more defined and intact rock is above R1 ISRM strength threshold. Further increasing until the average RQD of the fresh rock is established.
- Fracture spacing decreases sharply through saprolite and upper transition. An initial inflection point within the transition as similar spacing values are observed. A second minor inflection point is observed at the contact with the fresh rock as the average spacing within the fresh rock is established.
- Gradual increasing strength values through the transition as the intact rock becomes less weathered. Significantly increasing values are observed below the transition within the Fresh Rock.
- A wide distribution of JCR values through the transition, typically below a calculated value of 15 in the upper transition and 20 at the contact with the fresh rock.
- The lower and upper range of tested hydraulic conductivity values are plotted. The widest distribution of values are observed within the transition. The permeability is significant less in the overlying soils and saprolites, as well as the underlying the fresh rock unit.

Furthermore, the conceptual hydraulic conditions for a deeply weathered rock excavation is shown in Figure 7 (Abrahams et al, 2015). A large proportional of the groundwater storage is held considered to be within the saprolite, and the most permeable horizons through the transition. The primary control on hydraulic properties is the degree of weathering. Experience at operating mines shows a sharp response in groundwater elevation with mining, as the transition under-drains the saprolite and exhibits strong downward hydraulic gradients.

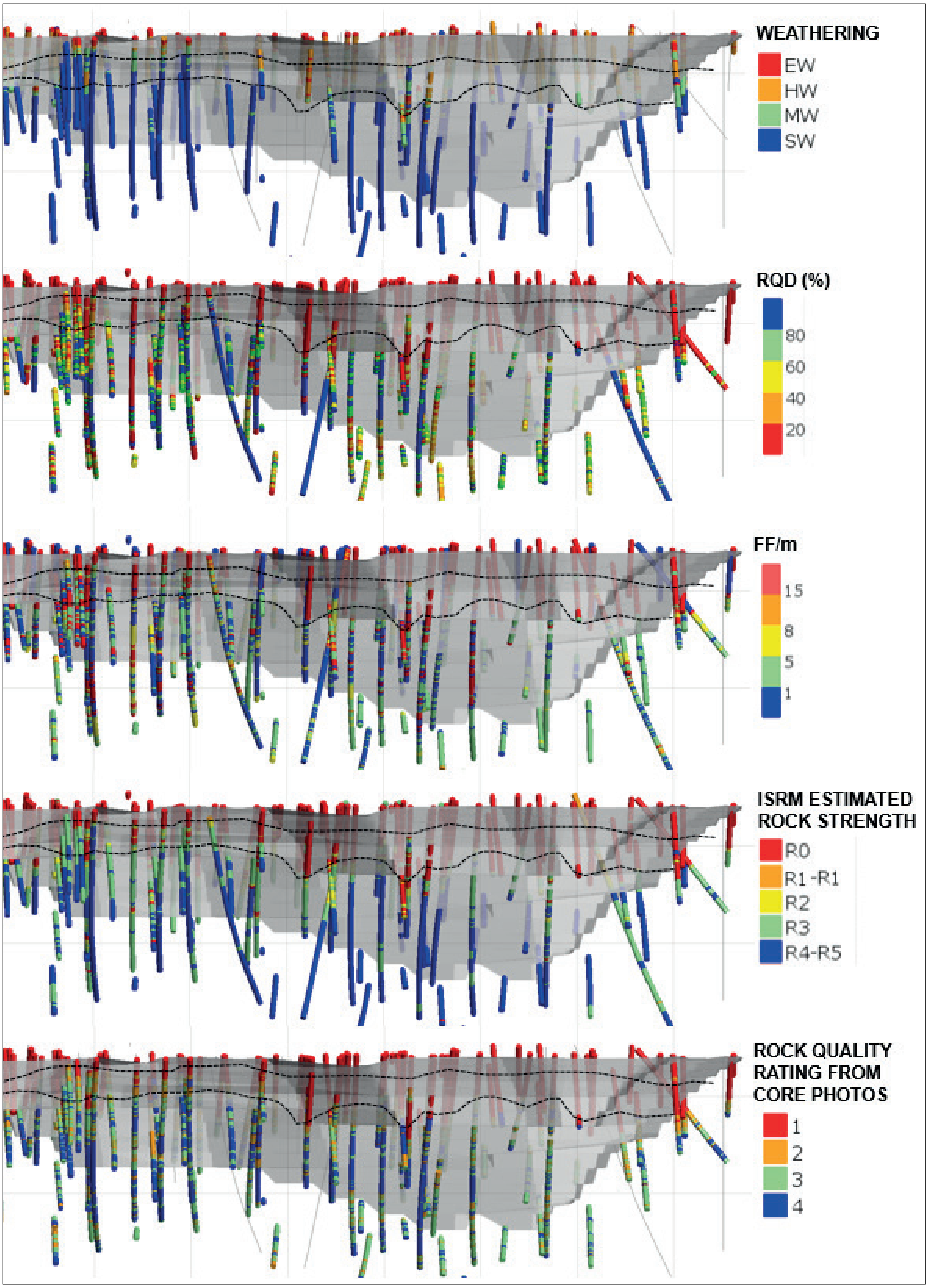

Figure 5: Variability of Selected Geotechnical Logging Parameters across a Deep Weathered Pit Slope. The above and Below Transition Contact is Shown in Black Dashed Lines

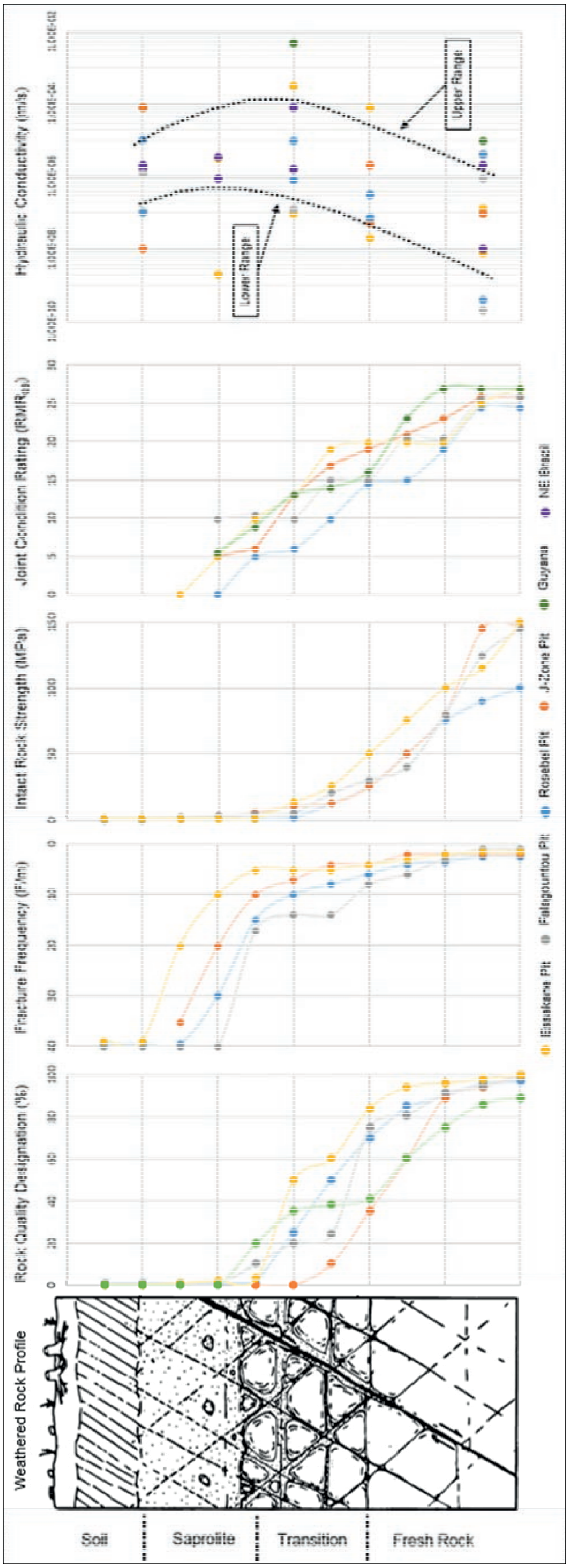

Figure 6: Site Specific Geotechnical Parameters Compared with the Weathered Rock Profile

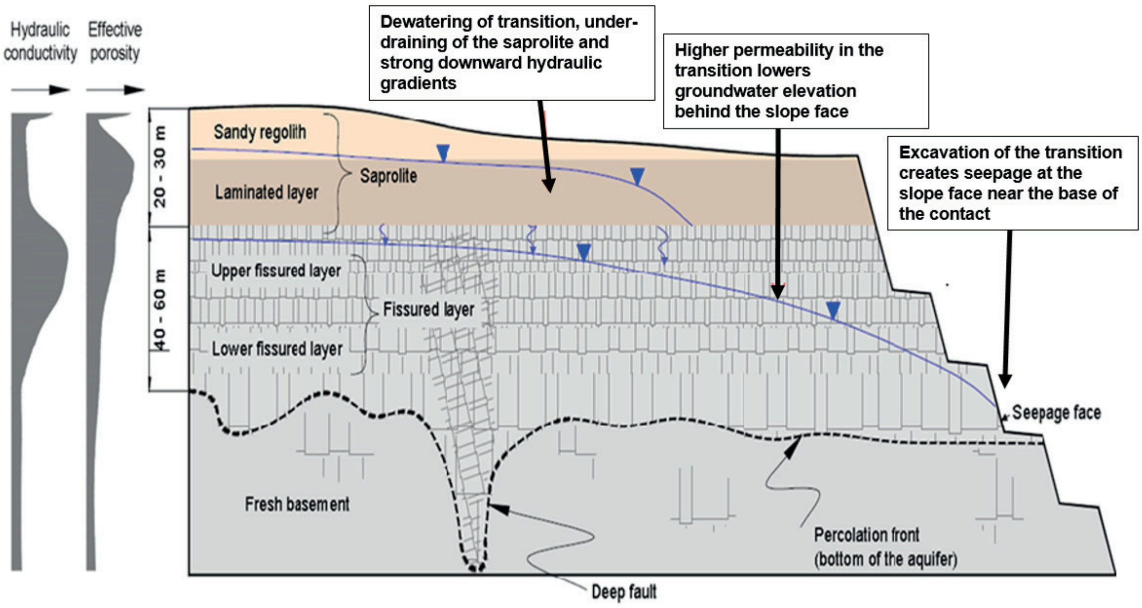

Figure 7: Conceptual Hydraulic Model through Deeply Weathered Rock Profile (Abrahams et al, 2015)

6. CHARACTERIZATION AND BENCH STABILITY REVIEW OF EXCAVATED BENCH SLOPES

A review of excavated bench slopes was conducted to determine primary geotechnical parameters that control the characterization of the transition zone, as observed. Two examples from operating mines are reviewed in this paper, including the Essakane Mine, Burkina Faso and Rosebel Mine, Suriname. These back-analyses have been carried order to improve the characterization for the slope design implementation and to understand the controlling parameters on stability performance.

CASE STUDY 1: NORTHWEST WALL, ESSAKANE PIT

Major structures have resulted in localised depression of the transition rock unit (Figure 8). Steeply dipping bedding structures and a shallower dipping basal joint set has resulted in significant topping instabilities across the slope, in addition to back-break from blasting. The weaker intact and inter-block strengths have reduced the supporting rock mass.

Historical geotechnical drillholes were reviewed to verify the characterisation of the transition unit (Figure 9). The drillholes show good correlation with the logged JCR values (and core loss) across the bench slopes with lower values exhibited within GT-01, GT-03, GT-04 and GT-05. The JCR values correlate well with depressed transition unit. Drillhole GT-02 correlated well with the saprolite, however, it is located sufficiently behind the slope and indicates improving JCR and rock quality behind the slope face. Estimated field strengths show reasonable correlation, with GT-03 encountering weak (R0 to R1) rock within the transition. The other drillholes indicate improved rock strengths which suggests that the weak inter-block shear strength is driving the observed toppling instabilities

Figure 8: Weathered Rock Profiles across the West Wall, Essakane Pit

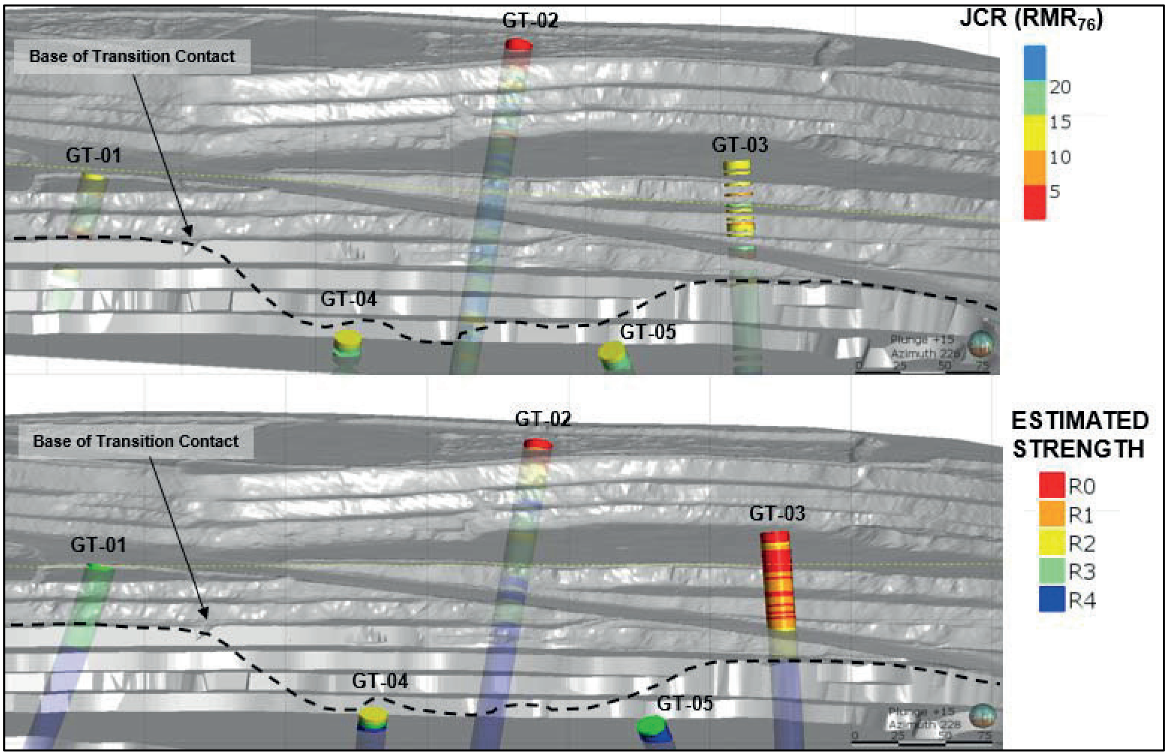

Figure 9: Joint Condition Rating (RMR76) and ISRM Estimated Strength from Geotechnical Logging across the West Wall, Essakane Pit

CASE STUDY 2: SOUTH WALL, ROSEBEL PIT

A thick saprolite unit overlies the transition rock along the South Wall of the Rosebel Pit (Figure 10). To date, significant surface water erosion and infiltration has resulting in localised slumping. To decouple the saprolite from more component (but weak) transition rock, a wider 20 m geotechnical catch-bench is adopted as part of the slope design. In order to implement catch bench at the saprolite-transition contact, the design relies on good characterisation prior excavation.

The pit is linear in geometry due an east-west fault-hosted mineralization, and geotechnical drillholes were spaced widely along the 1600 m pit strike length. The geotechnical drillholes were used to initially characterize the transition. Two geotechnical drillholes were widely spaced through the case study slope area (Figure 11). However, in order to refine the characterisation an evaluation of rock quality from exploration core photography was performed, and subsequently, qualitative ratings assigned (Figure 11). Ratings were assigned to intervals of rock based on the estimated rock hardness, RQD, fracture spacing and presence of major geological structures. This approach continues to rely on good field inspections of the exposed rock in order to verify the rock mass conditions and contacts, and to provide a feedback loop into the design implementation.

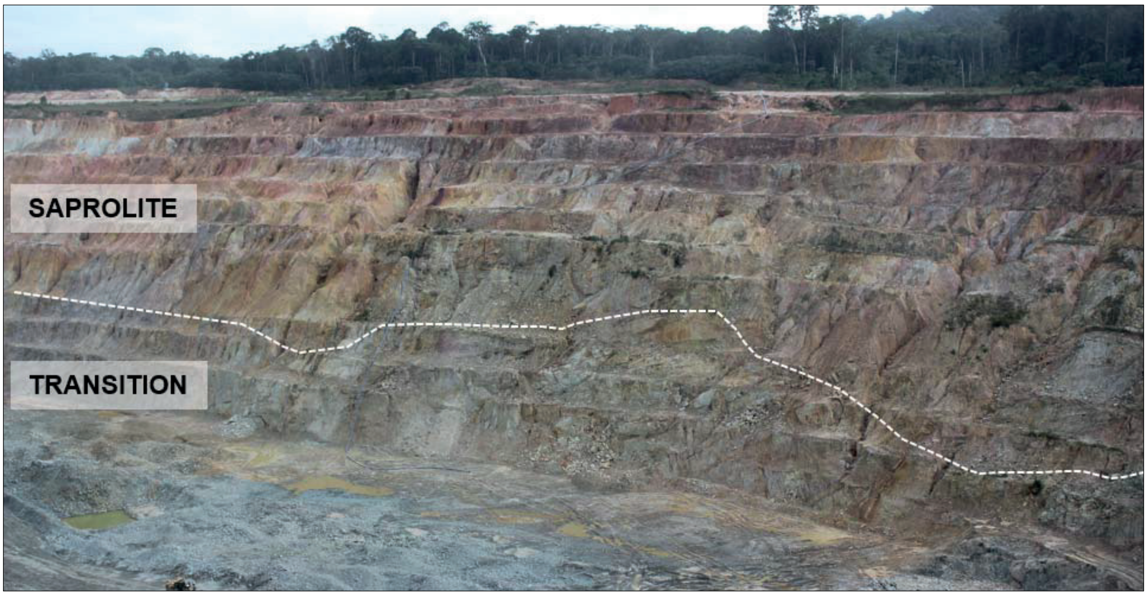

Figure 10: Weathered Rock Profiles across the South Wall, Rosebel Pit

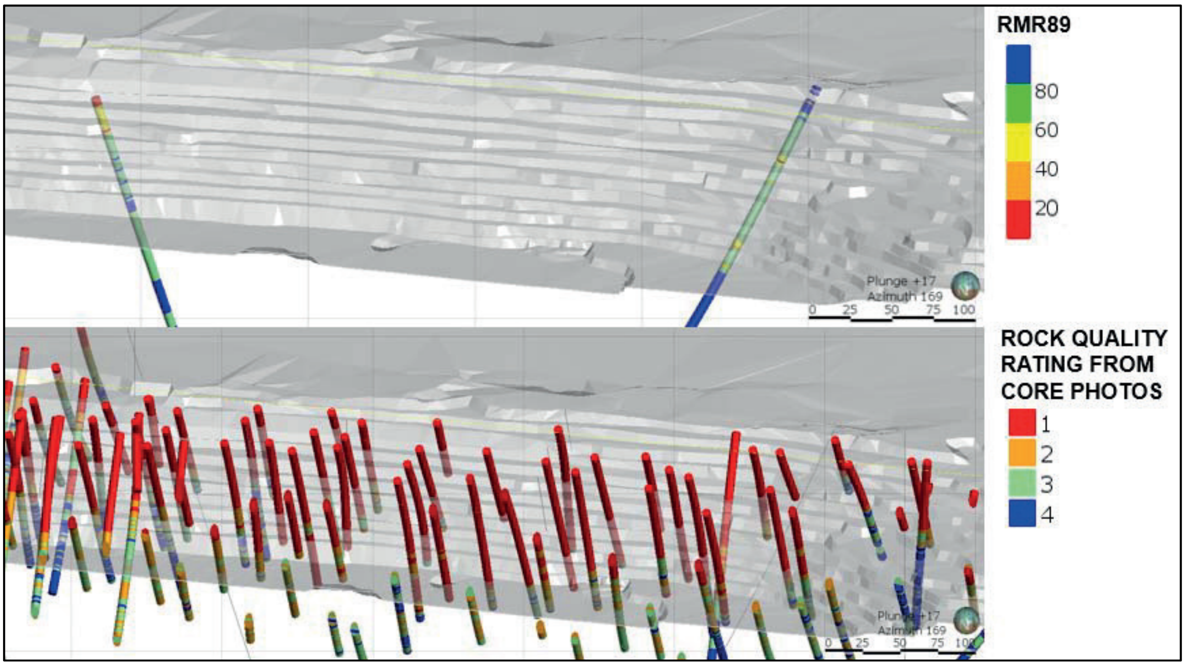

Figure 11: Location of Geotechnical Drillholes showing Rock Mass Rating (RMR89) and Qualitative Rock Quality Ratings from Exploration Core Photography across the South Wall, Rosebel Pit.

PROBABILISTIC BENCH SCALE STABILITY REVIEW

The geotechnical parameters that are considered to be controlling the performance of transition bench slopes can be evaluated probabilistically using the program SBlock™ (Esterhuizen, 2004). SBlock utilizes discontinuity input parameters to simulate the formation of key-blocks at the bench scale. The input parameters include orientation, spacing, persistence, friction angle, cohesion and the analysed bench configuration. Simulated key-blocks that are detached from a modelled bench slope generate a resulting distribution of catch bench and back-break widths reviewed against accepted probabilities of failure (POF). The results can be compared with as-built slope configurations for design verification.

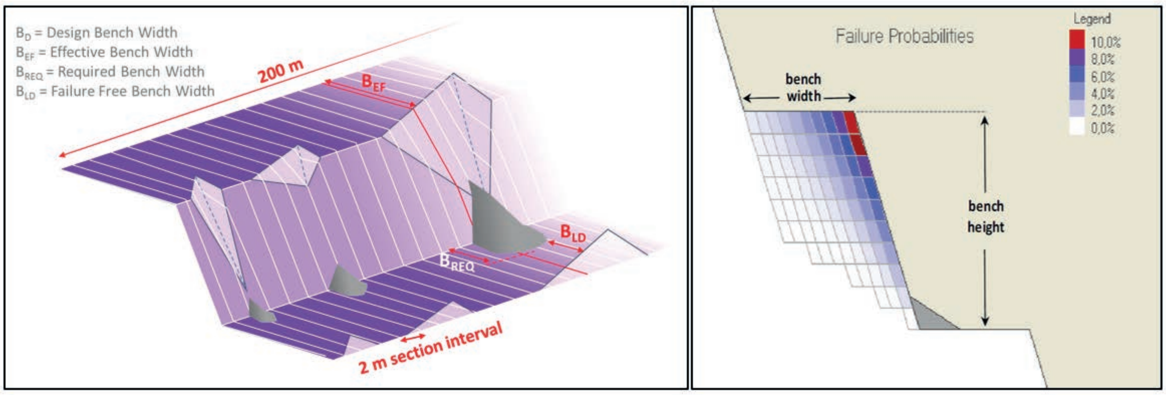

Figure 12: Schematic Showing S-Block Key-Block Formation and POF (Hormanzel, 2013)

As discussed in Case Study 1, the bench slopes along the Northwest Wall of the Essakane Pit have experienced significant toppling mechanisms. The intact rock strength shows improvement with depth as the rock becomes less weathered. The transition is more intensely fractured than the equivalent

Fresh Rock. SBlock simulations were completed to verify the implemented slope design (IRA = 35°, BFA = 80°, Bench Height = 10 m and Catch-bench width = 12.5 m), and to probabilistically assess back-break and catch bench widths for future bench excavation. The simulated catch-bench widths were compared against the as built slope profile and observed kinematic instabilities. The key input parameters including spacing and frictional strength were collected from the drillholes and bench face mapping.

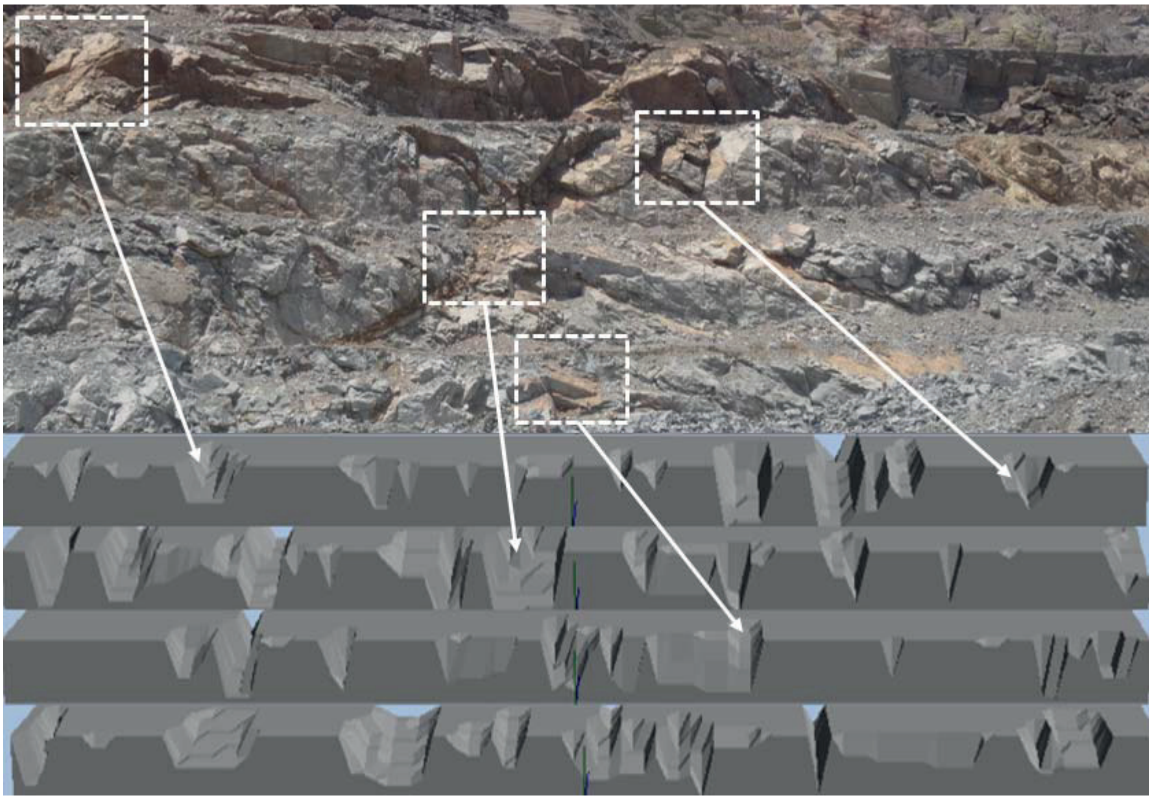

Figure 13: Transition Bench Slope Performance and the comparable SBlock Simulation

By simulating a model similar to the as-built conditions, the key discontinuity spacing and friction angle were able to be determined with confidence. These parameters were able to be compared with those used in the design. This refined parameters can be utilized in future excavation stability studies.

The equivalent fresh rock model is presented in Figure 14. Spacing and friction strength parameters were increased to represent the values determined from geotechnical logging and other fresh rock exposures in the pit. Discontinuity orientation and persistence were consistent. The results indicates that a steeper inter-ramp angle of 48 degrees was acceptable based on achieving a 14.5 m catch bench width with a 20% POF for a 20 m high bench height and 80° pre-split bench face angle.

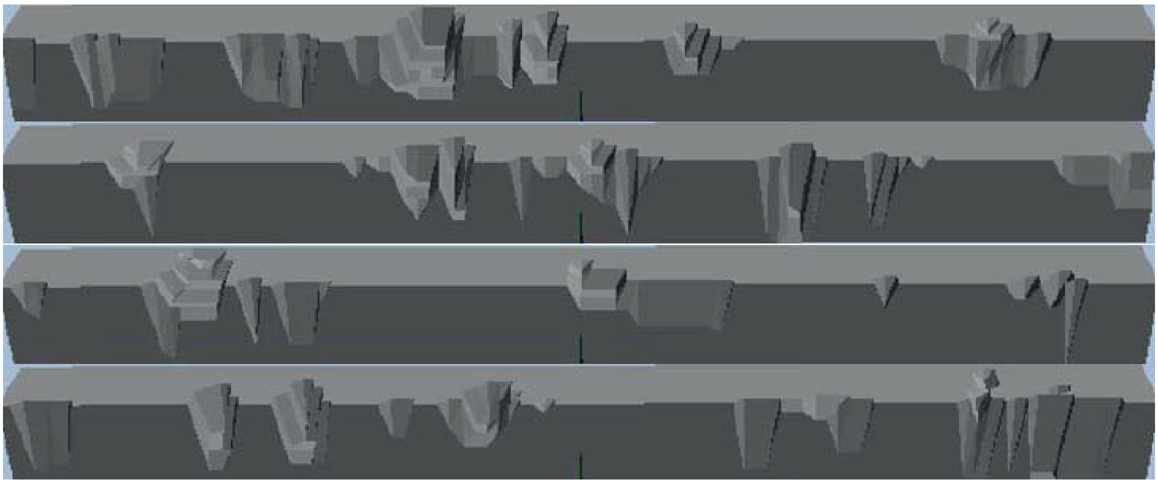

Figure 14: SBlock Simulation for Fresh Rock Bench Slopes

7. DISCUSSION

This paper presented a review of the geotechnical characterization and case-study stability performance for bench slopes designed and excavated in transition materials. The transition materials are difficult to characterize reliably by either soil mechanics or rock mechanics strength criterions. A gradual change from soil mass or weak rock mass toward a governing inter-block shear failure can be observed as the transition becomes structurally controlled.

The discussions on geotechnical characterisation highlight the importance of using all available data to develop a robust geotechnical model that can be relied on for slope design and then used to implementation. Furthermore, the value of continued verification as the new benches are exposed in the pit was presented. Particular importance is directed toward the accurate delineation of the transition contact surfaces with the overlying saprolite and underlying fresh rock in order to properly implement the slope design criteria.

Probabilistic analyses using the software program SBlock demonstrate a verification tool for as-built bench slopes configurations with consideration to the observed kinematic failure mechanisms. These analyses or similar should incorporated into the slope design feedback loop in order to implement appropriate slope configurations.

8. ACKNOWLEDGEMENTS

The author wishes to thank IAMGOLD for granting permission to allowing case study information to be presented in this paper. The author would like to also thank the geotechnical, hydrogeology, geology and mining teams at the Essakane and Rosebel Mines for their continued support.

9. REFERENCES

- Abrahams, G. Raynor, M and Mandisodza, K. (2015). Saprolite Design at the Rosebel Mine. Proceedings, Slope Stability 2015, South African Institute of Mining and Metallurgy, Cape Town, South Africa, 12-14 October. .
- Bieniawski, Z (1989). Engineering Rock Mass Classification. John Wiley & Sons, United States.
- Blight, G and Leong, C. (2012). Mechanics of Residual Soils. Taylor and Francis.
- Castro, L. Caravalho, and J. Sa, G. Discussion (2013) on how to Classify and Estimate strength of Weak Rock Masses. Proceedings from International Symposium on Slope Stability in Open Pit and Civil Engineering, Brisbane, Australia. 25-27 September 2013

- Deere, D and Patton, F. (1971). Slope Stability in Residual Soils. Proceedings from Panamerican Conference on Soil Mechanics and Engineering Foundation, Suan Juan, Puerto Rico, June 1971.
- Esterhuizen, G. (2004). SBlock v.2.01 User Guide and Reference Manual.
- Fookes, P (ed). (1997). Tropical Residual Soils: A Geological Society Engineering Group, Working Party Revised Report. The Geological Society Publishing House, Bath, United Kingdom.
- Fookes, P. Baynes, F and Hutchinson, J. (2000). Total geological history: a model approach to the anticipation, observation and understanding of site conditions. Proceedings from GeoEng2000: Internation Confernece on Geotechnical and Geological Engineering, Melbourne, Australia, 19-24 November.
- Hormazabal, E. (2013). Bench Berm Design using Proabalistic Keyblock Analyses. Proceedings from International Symposium on Slope Stability in Open Pit and Civil Engineering, Brisbane, Australia, 25-27 September 2013.
- ARANZGEO. (2017). Leapfrog Geo v.4.1.
- Major, G. Yuan, P. and Sharon, R. (2009). Optimizing Designs of High Slopes in Transported Materials and Residual Soils. Proceedings from Slope Stability 2009 Conference, Santiago, Chile, November 9-11, 2009.
- Martin, D and Stacey, P. (2013). Pit Slope in Weathered and Weak Rocks. Proceedings from International Symposium on Slope Stability in Open Pit and Civil Engineering, Brisbane, Australia, 25-27 September 2013