

## **Integrated Slope Stability and Dewatering Evaluation: Optimizing Slopes to Optimize Value**

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### **Abstract**

Many mines have saprolite or laterite soils in their pit walls. These soils, like many unconsolidated or semi-consolidated deposits, are highly susceptible to changes in the moisture content. In order for an open pit mine to have an optimized economic return, the pit slopes must be as steep as possible without risk of failure. This can be done through an integrated study of the hydrogeology, pit slope dewatering, and geotechnical stability.

The Aurizona mine, owned by Luna Gold, is located in Maranhão State, Brazil. The project sits on a peninsula that extends into the Atlantic Ocean, and tidally-influenced water exists less than 5km to the east and west of the mine. The Aurizona mine produced from 2010 to 2015 and is currently in a retooling period to allow for a mine expansion and modifications in the process circuit. The Aurizona mine will exploit gold resources contained in saprolite and an underlying tonalite intrusive rock. Studies performed in 2015 revealed a strong sensitivity between the steepest allowable pit slopes and the project economics.

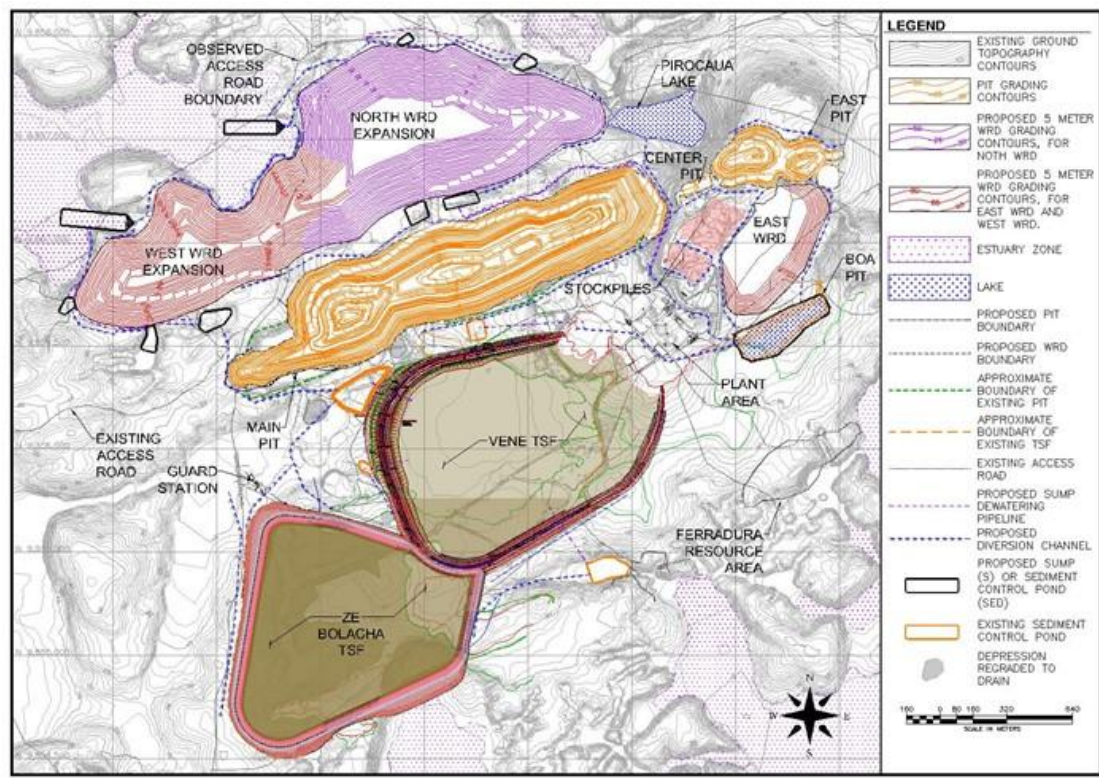
Global Resource Engineering (GRE) and Crux Engineering Group (CEG) conducted a study to actively optimize the saprolite slopes through an integrated hydrogeologic and geotechnical characterization and modeling effort. The program included a packer testing program to characterize the fractured rock aquifer, an aquifer testing program for the saprolite unit, and a geotechnical testing program to ascertain soil strength properties. Based on this information, groundwater flow models were created to determine not only the total dewatering requirements, but also the moisture content in the pit walls. CEG used moisture content profiles and soil testing data to optimize the pit slopes with the hard rock and the saprolite. The results of the study will be incorporated into the mine plans and upcoming revisions to a Feasibility Study.

Optimized pit wall angles are an essential element in overall project economics for the Aurizona Mine. The study reinforced the value of integrated dewatering and geotechnical studies even at early phases of project development by presenting the best possible stripping ratio (waste to ore) as early as possible in the mine development timeline.

Key words: Slope stability, groundwater modeling, saprolite

### **Introduction and Background**

The project consists of the Main Piaba pit; smaller center and east pits, a carbon-in-leach processing plant, two tailing storage facilities, and two waste dump facilities. Figure 2 shows the future site layout in the vicinity of Piaba pit.



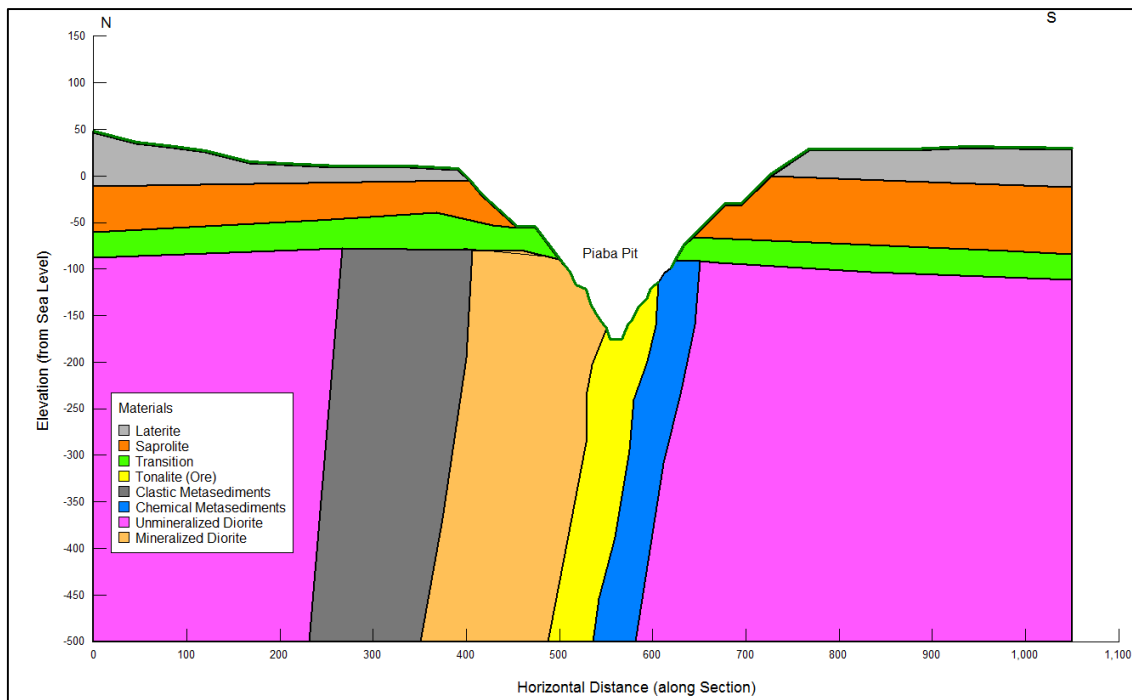
*Figure 2 Aruizona Mine Layout, With Piaba Pit.*

From 2010 to 2015, the mine exploited a laterite-saprolite hosted ore deposit and dug the Main Piaba pit down to the -17 meter (below sea level) elevation. However, in 2015 the reserves within the soft-saprolite were depleted and the mine was placed on care and maintenance pending further mine design and development to allow for exploitation of the hard-rock and transition zone hosted gold resource. The mine currently has a 6-year mine life, and plans to excavate the Piaba pit to -170 meters below sea level. The resource is open with depth and to the west, and with higher metals prices, the pit could go deeper and have a longer mine life.

### **Pit Geologic Model**

The Piaba pit is located within the structurally-controlled epithermal greenstone belt of the Sao Luis Craton. Typical of cratons, it is comprised of meta-sedimentary rocks intruded by igneous bodies. The area is dominated by a series of first-order ENE to WSW trending shear zones with a series of second order faults and shears that are oriented SE to NW. The shear zone system provided pathways for the development of the epithermal mineralization.

The igneous rocks that host the mineralization are bounded on both sides by metasedimentary units to the north and south. Locally, the geologic units resemble ‘layercake’ type with contacts that have been set to near vertical dip. Both the mineralization and lithologic units are oriented east-northeast and southwest. Sub-parallel strike-slip faults are reported along the geologic contacts and dip sub-vertically to the north, making the southeast pit wall the footwall and the northwest pit wall the hanging wall. Figure 3 provides a conceptual geological cross section of the project. Each of the bedrock units shown on the figure are described below.



**Figure 3** Conceptual Geologic Model of the Pit Area

**Unmineralized Diorite:** This unit is a quartz rich diorite rock with varying degrees of weathering.

**Clastic Metasediments (Greywacke):** A metasedimentary rock that is highly indurated and poorly sorted. It has been subjected to significant tectonic movements over a long period of time making it highly deformed, fractured, and/or veined.

**Mineralized Diorite and Tonalite:** The mineralized core is composed of diorite and tonalite. The mineralized tonalite is the ore host of the Piaba deposit. It is characterized by blue quartz and sulfides (primarily pyrite).

**Chemical Metasediments (Carbonaceous Metachert):** Slightly different metasediments populate the footwall. The chemical metasediments show finer grain size and less-pronounced bedding planes along thin laminations.

**Saprolite and laterite:** These formations overlie the hard rock formations. Saprolite is the resultant product of in-situ weathering of the parent rock and typically has material properties that improve with depth. The general texture of the saprolite is that of silty or clayey sand or clayey silt. However, the saprolite often retains some of the structures of the parent rock and may contain hard core stones of the parent material making the strength of the saprolite highly variable. Near-surface, the saprolite behaves as a soil, but improves to more rock-like behavior as the transition zone approaches.

**Transitions Zone:** The transition zone is a layer of mixed weathered rock and saprolite that has significantly higher hydraulic conductivity than the saprolite above or the harder rock below.

### Project Challenges

The project economics are very sensitive to the slope angles within the saprolite and laterite formations while understanding the geotechnical strength properties that dictate the slope angles within these deposits is difficult. Aggressive pit slope dewatering is required to enhance the pit slope stability and resulting pit slope angles within the saprolite. This can be accomplished by draining the transition zone.

## **Methods**

Determining the optimal saprolite slope angles involved a two-step process which included 1) determining the maximum possible dewatering achievable by reasonable methods, and 2) determining the resultant pit slopes based on the dewatering effectiveness.

### ***Pit Dewatering***

Pit dewatering will be accomplished through in-pit sumps, and horizontal borings (fan drains) drilled 100 meters out into the transition zone from a continuous bench located on top of the slightly-weathered or fresh rock. These fan drains allow for the effective and rapid dewatering of the saprolite formation beneath the pit walls.

In the field, an aquifer test program and a packer test program provided data on the conductivity of the key formations. Based on this data, the effectiveness of dewatering was ascertained with two methods; MODFLOW (Surfact) (HGL 2006) groundwater model to ascertain the regional water level and the saturated flow dynamics of the pit, and a Vadose/W (Geostudio 2012) unsaturated flow model to simulate the seasonal moisture content changes in the laterite and saprolite.

The MODFLOW model simulated the three-dimensional flow dynamics, the impact of regional faults and fractures which act as preferential flow pathways, and the spatial impact of the fan drains. It also simulated the impact pit dewatering will have on local lakes (such as Pirocaua, see Figure 2), and estuaries of the Atlantic Ocean.

However, the MODFLOW model was not sufficiently precise to simulate the impacts of seasonal rainfall on the moisture content within the saprolite and laterite in the pit walls. As a result, GRE created a Vadose/W model for the pit slopes. The Vadose/W model simulated the daily climate conditions falling on laterite and/or saprolite soils. It utilized representative soil water characteristic curve data that was taken from similar sites and applied to the model, and it used the results from the MODFLOW model to define the regional water table.

### ***Saprolite Slope Stability***

As mentioned above, the focus of the geotechnical stability study focused on saprolite and laterite slopes.

### ***Ascertaining a Saprolite Weathering Profile***

Typical bedrock weathering profiles, with associated weathering categories (ISRM, 2014) for pit slopes in saprolite are shown in Figure 4. Laterite is weathering category VI, Saprolite is IV, to V, and transition is category III

It is assumed that the shear strength of saprolite profiles increases with a decrease in weathering, and therefore, an attempt was made to identify the ‘completely’ and ‘highly’ weathered rock at Piaba Pit based on criteria by International Society of Rock Mechanics (ISRM, 2014) standards. Once subdivided, the category IV and V saprolite could be treated separately in the stability evaluations. Unfortunately, a review of the project boring logs suggested that no clear distinction is evident within the saprolite logging that would allow the subdivision of the mass into separate weathering categories. Moreover, weathering and sloughing of the saprolite exposures within the current pit prevented accurate pit wall mapping of the saprolite weathering profiles.

**Figure 4** Conceptual Geologic Model of the Pit Area

As a result, individual saprolite soil samples collected for the laboratory testing campaign were subdivided during the sampling, testing, and test evaluation process based on weathering and ultimately, a gradational strength profile for soils was developed based on the assumption that the saprolite strength varies linearly with depth.

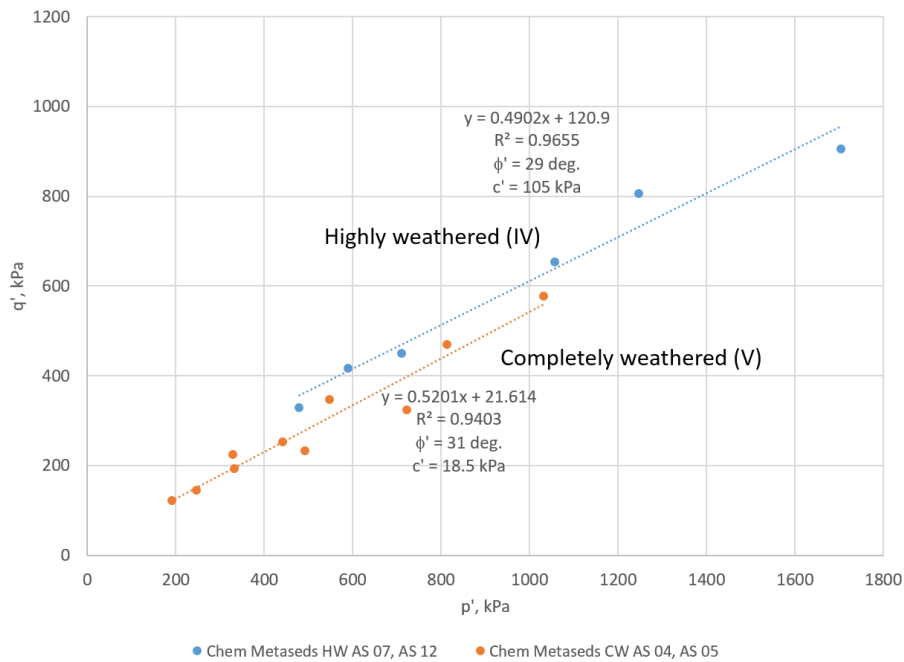
Relatively undisturbed samples of saprolite were collected throughout the life of the project and tested at reputable testing laboratories in Brazil. Initially, block samples were collected using a backhoe. Additional samples were collected by first excavating shallow test pits within the saprolite of the existing pit walls and then by pushing thin-walled (Shelby) tubes into the soil matrix. Representative samples from the different geological lithologies tested and the samples were distributed throughout existing pit shell.

Consolidated undrained triaxial testing (CUTX) with pore water pressure measurements were completed on all samples, and consolidation pressures were chosen based on the probable change in in-situ stresses during the pit excavation.

**Results**

***Geotechnical Testing***

Test results from these studies were grouped and reduced together for the purpose of establishing the saprolite shear strength of the different weathering categories and lithologies (Figure 5). In some cases, the individual tests were deemed invalid based on shearing along a pre-existing plane of weakness within the samples. The Figure 5 shows the p-q plots for the CUTX tests and these plots were used to establish the Mohr-Coulomb shear strength estimates shown in Table 2.



**Figure 5** Example p-q plot for the Saprolite Testing at Piaba Pit.

**Table 2** ‘Drained’ shear strength parameters generated by the CUTX testing

Lithology	Weathering	$\phi'$ , deg	$c'$ , kPa	Notes
Chemical Metasediments	Comp. Weathered	31	18.5	
	Highly Weathered	29	105	
Clastic Metasediments	Comp. Weathered	31	5	Only one valid sample for testing. Therefore, we assumed and used the strength values from the Chemical Metasediments.
	Highly Weathered	NA	NA	
Diorite	Comp. Weathered	26	27	
	Highly Weathered	33	132	
Mineralized Diorite	Comp. Weathered	32	0	These values are indicative of residual soil and not saprolite. Therefore, they were not used.
	Highly Weathered	28	81	

The testing results confirm that decreased weathering results in a constant friction angle and an increasing ‘cohesion’ intercept of the materials (overall; greater strength). The increase in cohesion intercept with a decrease in weathering is representative of a stiffer and less weathered soil matrix while a relatively consistent friction angle is the result of a near-constant mineralogy and grainsize of the matrix through the weathered horizon.

**Field Conductivity Testing**

Aquifer testing and packer testing was required to characterize the aquifer dynamics and dewatering effectiveness. The testing program had the following results by rock type or alteration type:

- Laterite:  $10^{-3}$  to  $10^{-4}$  cm/s
- Saprolite:  $10^{-5}$  cm/s
- Transition Zone: Variable, from  $10^{-3}$  cm/s to  $10^{-5}$  cm/s depending on clay content, degree of weathering.
- Fractured fresh rock: Variable, from  $10^{-3}$  to  $10^{-5}$  cm/s
- Unfractured fresh rock: Consistently  $<1 \times 10^{-6}$  cm/s.

As a result, it appears that, due to its higher conductivity, the transition zone can be used as an “underdrain” for saprolite and laterite slopes. However further testing is required particularly to identify if the fresh rock is sufficiently fractured to act as a preferential pathway for saltwater intrusion into the pit.

**Groundwater Modeling**

The MODFLOW models predicted that the Piaba pit would receive ~50 L/s of groundwater inflow. This value increases in the 5th year of mine life and decreases in later mine life due to the depletion of hard-rock storativity. Fan drains were found to be effective. They decreased the phreatic surface beneath the pit walls by ~3.5 meters (compared to the case without fan drains). However, the regional-scale MODFLOW model proved ineffective at predicting close-in changes in the soil moisture content in the pit walls.

The Vadose/W model, with a more rigorous management of climate conditions and unsaturated flow, proved effective at predicting the seasonal variations in moisture content that could prove critical to saprolite slope stability. Figure 6 is a screen snapshot of the migrating wet fronts predicted in the Vadose/W modeling.

The moisture content profiles at various times (reflecting worst-case conditions) were provided to Crux for use in the geotechnical modeling.

*Figure 6 Example Result: Perched Seasonal Moisture in Pit Slopes*

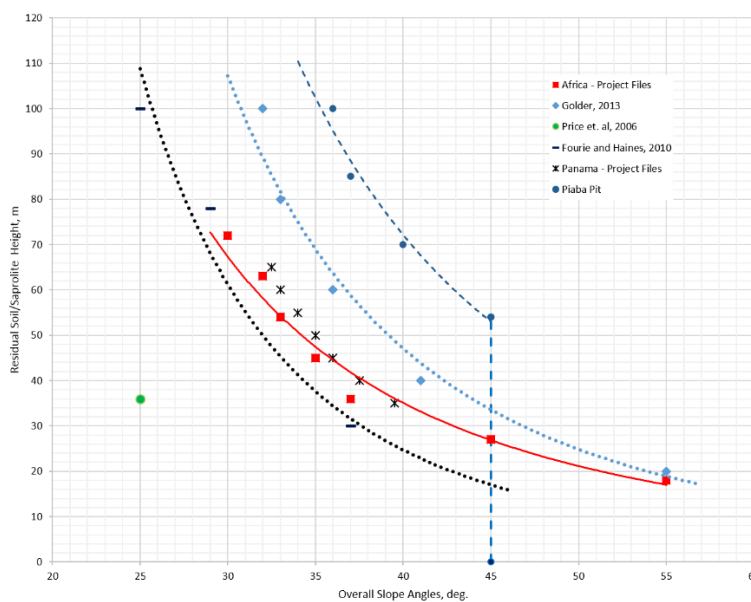
**Pit Slope Stability Modeling – Inter-ramp Angles**

The pit slope geotechnical modeling followed recommendations by Read and Stacey, 2009. In the saprolite, where the rock mass strength controls the pit slope stability, inter-ramp angles were determined by completing a slope stability analysis using design charts and computer simulations. Once inter-ramp angles were established, the combination of bench-face angle and bench widths were varied to achieve the desired inter-ramp angles. Final slopes were determined in conjunction with ramp layouts provided by the mining engineers.

Finally, the overall pit slope angles were confirmed using a limit equilibrium method. The overall slopes encompassed all rock types, the inter-ramp angles, and geotechnical berms. Design assumptions required a factor of safety of 1.3, a fully-drained pit wall, and static conditions (a reasonable assumption in a region with low seismic risk).

**Conclusions**

Comparatively steep saprolite slopes analyzed and found to be stable. Figure 7 shows representative results (some lithologies could be steeper while others should be shallower) as compared to other saprolite slope angles in recent work and/or published sources.



*Figure 7 Comparative Saprolite Pit Slopes*

Results of the stability modeling performed on the fully-drained slopes showed that saprolite pit slopes of modest height, could stand as steep as 45 degrees and meet the project safety factor requirements. As the overall slope heights increase, the corresponding stable slope angles decrease; which is reasonable. Comparison of the Piaba Pit results to those shown in Figure 7 suggest optimistic results. This is due to the following:

1. The project benefited from a relatively large database of strength values at the PFS level;
2. We applied a strength model which increased in depth from the completely weathered strength results to the highly weathered strength results rather than choosing one value for the saprolite which would be sufficiently conservative to represent the entire saprolite thickness; and
3. The pit slopes were effectively dewatered using fan drains; whereas, each of the other case histories shown in Figure 7 included the effects of water within the slope designs.

The project showed that an integrated dewatering and stability model early in mine life can yield significant improvements in project economics, making it an attractive investment for design stage mining projects. As the project proceeds towards design, the dewatering and stability assumptions will be confirmed through more hydrogeological and geotechnical testing and field trials of the horizontal drains.

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### **References**

- Deere, D.U. and Patton, F. D. (1971) Slope stability in residual soils. In: Proceedings of the Fourth Panamerican Conference on Soil Mechanisms and Foundation Engineering, American Society of Civil Engineering 1, 87–170.
- Fourie, A. and Haines, A. (2010) Obtaining appropriate design parameters for slopes in highly weathered saprolites. Newsletter of the Australian Centre for Geomechanics. Vol. 34. Pgs. 12 16.
- Fredlund, D.G., Rahardjo, H. and Fredlund, M.D. (2010). Unsaturated Soil Mechanics in Engineering Practice. John Wiley and Sons. 926 pgs.
- Geostudio 2012. Vadose/W. Finite-Element Groundwater Flow and Seepage Model with Climate Function Geostudio, 2012, Alberta, Canada.
- Golder Associates. (2013) Pit slope design for Bombore Project. Technical memorandum to Orezone Gold Corporation. 9 pgs. plus figures
- HGL 2006. MODFLOW-Surfact Groundater model. HydroGeoLogic, Inc, Reston VA.
- International Society of Rock Mechanics (2014) The ISRM Suggested Methods for Rock Characterization, Testing and monitoring 2007-2014. Edited by Resat Ulusay. Spring Publishing. 293 pgs.
- Price, J., Haines, A., Baidoo, I. and Varaud, O. (2006) Design considerations for the Damang Open Pit Expansions. The South African Institute of Mining and Metallurgy International Symposium on Stability of Rock Slopes in open Pit Mining and Civil Engineering. Pgs. 239-264.
- Read, J. and Stacey, P. (2009) Guidelines for Open Pit Slope Design.