URUCUM Mine: Rockfall protection and monitoring system

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ABSTRACT: The access to Urucum mine is at the base of the Morraria de Urucum, composed of sedimentary rocks, a very steep rockface. Several rockfalls events in the past required that the company take action to mitigate risks, leading to a diagnostic and protective measures. Initially, the analyzes were based only on a point cloud, due access restrictions related to the pandemic period, resulting in a preliminary design of rockfall barriers and drainage. With the conceptual design, an extensive field mapping was performed, and the project revised, culminating in a drastic reduction of necessary interventions. The optimization it was possible through identification of differential weathering in the jaspilite strata, which allowed a new geomechanical model, better probabilistic analysis of block size distribution and thousands of rockfall simulations. This case is an interesting example of how the use of modern tools helps in projects, but it shows that they should be used with caution.

Keywords: Rockfall, field mapping, point could, rockfall barrier, probabilistic analysis.

1 PROJECT AREA CARACTERIZATION

The area of this study consists of a manganese underground mining plant, the Urucum Mine, located in the city of Corumbá, Midwest region of Brazil, close to the border with Bolivia. The mean coordinates of the area are in UTM 435.255 E and 7.878.7684 S (WGS84), and the map with its location is presented on Figure 1 (a), a Google Earth image.=.

Upslope of the main entrance of the underground mine the Morraria Urucum is present, a natural slope with more than 300 meters high that can be divided in 3 homogenous regions, see Figure 1 (b): a) *Crest Region* where the slope is about 50º of inclination, there is top soil, some isolated rock faces b) *Rockface Region* where a fractured and vertical rock slope is present (jaspilite) and c) *Base Region* a part of the slope where the inclination is about 20~30° and one can find dense forest vegetation and top soil, a talus type formation. In addition, on Figure 1 (c) the vertical rockface can be observed on frontal view.

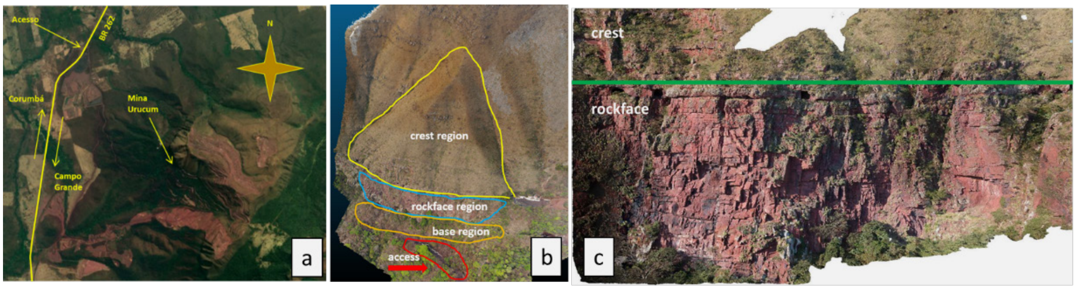


Figure 1. (a) location of the mine and slope configuration, (b) slope sectors and access and (c) vertical rockface, main source of rockfall.

1.1 *Geological and instabilities context of the Morraria Urucum*

The deposits of iron and manganese around the Municipality of Corumbá, in the portion of interest of the project belong to the Jacadigo Group, mainly sedimentary deposits with rocks of sub-horizontal attitude (Walde & Hagemann 2007). The typical geological cross-section of Morraria do Urucum, presented by Barbosa & Oliveira (1978), Dorr II (1945), Trompette et al. (1998) and Walde & Oliveira (1980), has its base composed of layers of arcosean, manganese or ferruginous sandstone. On top of that the first layer of manganese oxides can be found, with 1 to 6 m thickness, which is superimposed by ferruginous arkoses on which the second layer of manganese oxides occurs. Towards the top there are several levels of banded iron formations amidst a thick pack of ferruginous, locally non-ferruginous arkose.

The top of the unit is marked by banded iron formations composed of alternating layers of reddish jaspilite and levels of black hematite iron ore, which gives it the appearance of a chemical rhythmite. Granite pebbles and blocks (> 1m³) occur in the iron ore layers, evidencing the environment and glacial to periglacial deposition, the presence of the ice layer could have prevented the oxygenation of the waters by the atmosphere and created sufficiently reducing conditions to favor the precipitation of manganese. Subsequent melting could increase water oxygenation and thus make the environment favorable for iron precipitation, and the main geological cross-section can be seen on the Figure 2.

The composition of different rocks conditions the morphology of the site. The slope formed by arkose has high verticality, in contrast to the slope above the crest, composed of iron formation. The iron formation has distinct minerals (iron and silica) that dilate in different proportions due to physical weathering processes, generating voids and planes of weakness that accelerate the erosion process. On the other hand, the arkose of the verticalized slope is composed of sand and silt with carbonate cementation, forming a uniform rock that exhibits low rates of degradation, producing intact rock blocks.

In the specific case of the Urucum slope, there are two main types of instabilities that were identified, the detachment of rock intact boulders from the vertical face and rolling of blocks from the region above the crest. The first failure model is conditioned by the families of fractures of the rockface, and can be activated by the water pressure on the joint as wall the differential weathering. A rolling process is entirely dependent on where and how the rock nests/outcrops are place over the crest, and the movement can be initiated by the same reasons. Below on Figure 2 a basic drawing illustrates both mechanisms.

As told before, this slope is right above the main access to the mine itself as well other facilities of the mining company on site, exposing workers and equipment to rockfall hazard. In order to reduce the risk, this study have been conducted, to identify the blocks and propose a protection solution.

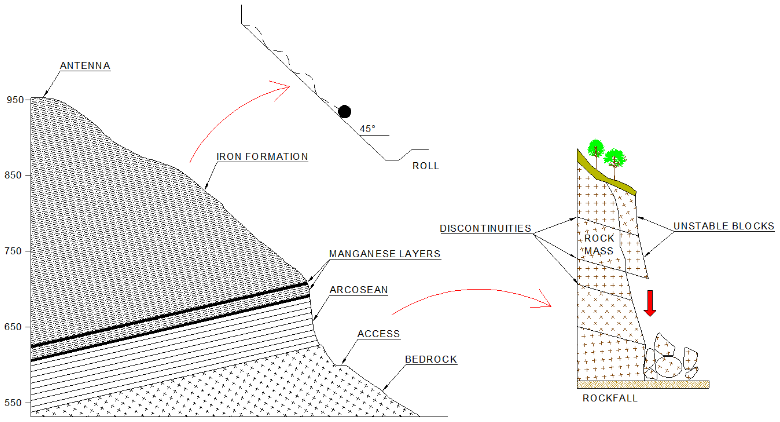


Figure 2. Geological Cross Section of the Morraria Urucum (authors) and main rockfall mechanisms.

2 RISK ANALYSIS AND CONCEPTUAL SOLUTION

In this particular project the design of the final solution has been developed by following a sequence of steps, preliminary analysis, the devolvement of a conceptual project, detailed field inspections and finally the final design of the solution, to achieve the best cost/effective solution possible.

The first step of development was a preliminary analysis, including a risk map for the area, taking into account the probability of occurrence, potential damage and the number of exposed persons. On the current paper, only an overview of this step shall be presented, for context purpose.

The probability of occurrence has been estimated by the slope characteristics and the potential damage was calculated with the traffic and operations, computing time travel, number of persons, total exposed time and also the especial probability of presence on the area, The vulnerability was defined according to Bell & Glade (2004), which defines that impacts of 14 kJ are considered fatal.

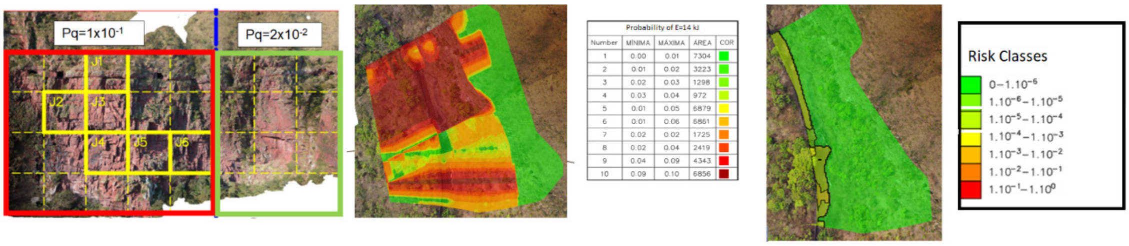
Due the COVID pandemic restrictions, no site inspection was allowed in the beginning of the project, so the first phase was made using a digital surface model (DSM) with point cloud generated by aerial photogrammetric restitution to identify and quantify the rockfall source zones.

The slope face and crest were detailed analyze, by the means of the only available information by the time, the point cloud. The goal was to sectorize the slope into homogeneous block size windows, to allow rockfall simulation, in order to define the statistical distributions of block sizes. In total 27 windows were defined (Figure 3), classified into 6 blocks mass sizes, enabling rockfall analysis – energy definition, velocity, impact height and most probable trajectory. This detailed analysis was possible due the high definition of DSM on the rockface. Unfortunately, the slope crest has a DSM with lower resolution, capable to define the outcrops but.

The product of this initial analysis were several maps showing the probability of impact, the impact heights and also the risk that the access was submitted. All this information was apply to facilitated the result interpretation, and most important, define a conceptual solution and to plan all the field inspections, in order to answer the main question evaluated on the preliminary analyses. Below on (Figure 3) the most important maps are presented, the sectorization of the slope with failure probability, the probability of impact with energy >14 kJ and the final risk of the access, whose lasses were defined based on Australian Geomechanics Society [AGS] (2007).

To assist the mining company teams to access which level of risk is acceptable Bell et al. (2006) and AGS (2000) publication were consulted, where level of acceptance around the world are presented. The definition of acceptable risk in every area is a management decision, but generally worldwide the tolerable levels of risk are around 10-5 and 10-4, so is possible to say that the Urucum Mine access is under an intolerable risk, demanding mitigation measures.

The conceptual solution for this slope was defined as implementation rockfall barriers with a parallel alignment to the main access, since the slope stabilization would be a very difficult solution, due the costs and access on the face. Based upon a distribution analyses of rock volume on each window, 4 solution scenarios were proposed, quantifying residual risks and costs, basically by changing the barrier energy class and height, as can be seen on Table 1.



Probability of E=14 kJ

Number	MÍNIMA	MÁXIMA	ÁREA	COR
1	0.00	0.01	7304	🟩
2	0.01	0.02	3223	🟩
3	0.02	0.03	1298	🟩
4	0.03	0.04	972	🟩
5	0.01	0.05	6879	🟨
6	0.01	0.06	6861	🟧
7	0.02	0.02	1725	🟧
8	0.02	0.04	2419	🟥
9	0.04	0.09	4343	🟥
10	0.09	0.10	6856	🟥

Figure 3. Inspection windows and occurrence probability and probability of impact with energy>14 kJ and risk map of the access.

Table 1. Conceptual Scenarios for rockfall protection systems.

Scenario	Residual risk	Barrier Energy	Height	Cost U$
01	Very low	10.000 / 8.000 kJ	10 to 8 m	2,5 Mm
02	Low	10.000/5.000/3.000 kJ	7 to 10 m	1,75 Mm
03	Low	10.000 / 3.000 kJ	6 to 10 m	1,90 Mm
04	Medium	3.000 / 5.000 kJ	6 to 9 m	0,65 Mm

From the source zones located on the slope crest, impact energies on the access zone was higher than any reasonable engineering solution could absorb (up to 100.000 kJ), and barrier lines on the slope crest was also demanded on this project phase. The solutions defined on this project phase are summarized on Figure 4. A drainage system was designed to avoid water inflow to the vertical rock face.

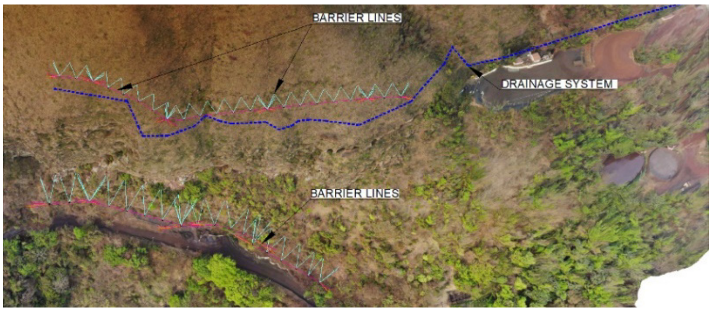


Figure 4. Solutions defined on this project phase.

3 FIELD INSPECTION

When COVID pandemic restrictions where reduced, a detailed field inspection was carried out using rope access. The inspection itself was a challenge due the slope dimensions, more than 300 meters height, a vertical face with several debris and very poor access points.

The solution was to apply rope access techniques and 2 inspection teams, dividing the total area into small regions for each team. The filed work took place in 5 days and in this period was possible to collect technical data all along the slope, Figure 4.

The previous rock masses mapped by the point cloud on the crest region, resulting in a volume up to 70 m^3, of heavy itabirite. As itabirite are often hard and compact rocks, bigger boulders were considered on the first project phase, as already pointed out, which lead to solutions extreme robust and costly. However, in the site inspection a different weathering was verified between the thin layers (~1cm) of reddish jaspilite and black hematite. Structural geological conditions that split big boulders are confirmed in field, with vertical tectonic fractures and sedimentary bedding planes, but these differential weathering process culminate in a block disaggregation during the rockfall process. This process justifies the gentil slope at the crest part (~35º). And this reduction reduces dramatically the energy involved on the process. Figure 5 shows the inspected outcrops and jaspilite / hematite mapped on field.

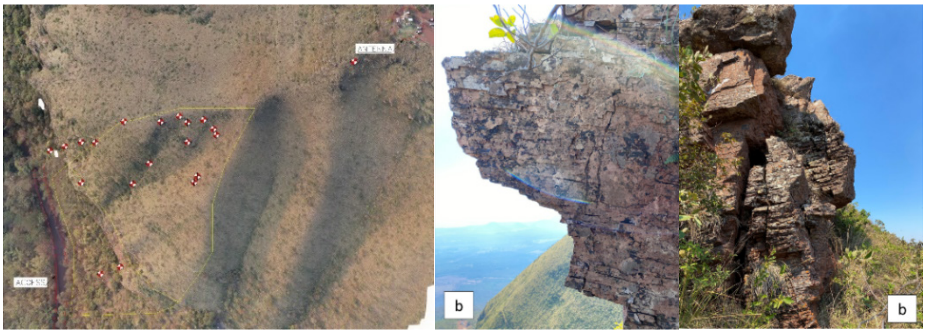


Figure 5. Rock masses position and detail of its fractured conditions on the crest.

The rupture mechanism that conditions the detachment of the blocks on the vertical rock face was confirmed as initially predicted (drop and toppling). Stratification is favorable (about 13 degrees upstream), but the evolution of instability processes culminates in the formation of negative slopes, the greater the more intact the outcropping rock stratum. Different types of negatives were identified in the field: (i) staggered and (ii) massive.

Type (i), staggered, presents a sequence of displacements of submetric blocks, arising from the structural accommodation of verticalized fractures and the failure by traction of some stratified mineral levels. This set of factors ends up generating a staggered geometry of the negative, releasing small block in every event. Type (ii) massive, are the negative ones that occur in more resistant strata, and culminate in the individualization of larger potentially unstable blocks. This type is much less frequent than the first, during field inspections 5 of these negatives were identified. Both types of negatives are presented below.

Figure 6. Typical condition of the rock face.

The inclined slope is mainly formed by rock debris, very permeable, so any drainage solution implemented on the top of the terrain, would not be effective, so it was suppressed from the concept.

4 FINAL DESIGN SOLUTION

After the filed inspections were concluded, block size distribution was reviewed on the probabilistic rockfall simulations. Rockfall dynamic barriers was designed for boulders from the crest and instabilities type (i) from the rockface, and an alarm system was designed for instabilities type (ii).

The new results have showed that to intercept and hold all the block mass type (i) the barriers should have 3.000 kJ absorption capacity, with heights between 6,0 and 9,0m dependent on the project region.

For the massive type (ii) blocks, a monitoring system was design in order to be used as an alarm system by the mining expert team. This monitoring system is composed crack meters to monitor in real time any kind of movement. Initial displacement rates were established as critical, based upon Early Warning Systems (EWS), referenced on Bertolo (2017), Carlà et al. (2019), Sättele et al. (2016) and Tamburini & Martelli (2006), which would be calibrated along time.

Figure 6. Final designed solution.

5 CONCLUSION

Access to Urucum Mine tunnel portal is subjected to a rockfall hazard whit several sources along a 300m height rock slope. This paper showed the rockfall diagnoses and protection measures design. The initial concept was developed based on DSM models without field inspection, and the solution at the time basically rockfall barriers and drainage system. After a detailed field inspection reveals a differential weathering process in the Jaspilite / Hematite outcrops, and it reduces significantly the rockfall energies, resulting in a new design. The drainage was removed and the number and energy capacity of rockfall barriers reduces significantly, resulting on an overall costs reduction 50~60%, in comparison with the initial designs. This paper highlights that the use of new technologies is a significant improvement to geotechnical engineering, and helpful for project developments, but should be always be considered as a tool. Detailed field inspection, and accurate engineering judgment was always a key importance for geotechnical solutions.

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