Design Review of the Remediation Project of a Highly Weathered Open Pit Wall from a Closed Iron Ore Mine in Brazil

José Allan C. Maia, Teófilo Costa
Vale S.A., Belo Horizonte, Brazil

Anderson Fonini, Felipe Gobbi, Ricardo Menezes, Gonçalo Sonaglio, Fabiano Madrid
FGS Geotecnia, Porto Alegre, Brazil

ABSTRACT: In the late 90s, the excavation of an open pit mine was initiated in the Iron Quadrangle, a rich iron ore region situated in southeast Brazil. During years of excavation and mining duties, but especially after reaching its maximum depth, many instabilities occurred in the north wall, which presents about 500 m height and overall slope inclination that fluctuates between 30° to 35°. In the 2010s, a Real Aperture Radar and a series of prisms distributed across this wall indicated a total displacement of about 65 cm in 120 days during severe rainstorms. More recently, in the 2020s, InSAR data have shown that the displacements are still occurring after many slope failures, especially during the rainy season. As a result, the extensive erosion process accelerated the wall unloading generating a net of several unstable surfaces (comprising millions of cubic meters) controlled by the regional structural setting. Thus, during the design review of the remediation project, according to the reduced data available, several analyses were conducted to confirm the geotechnical parameters obtained from field and lab tests and assess the failure depth from back analyses. Finally, the design review service shows that the remediation proposed by the basic design could no longer address effective treatments for the decommissioning design of the north wall, but the remediation actions are still valid.

Keywords: Decommissioning, Surface mining, Design review, Complex geology, Tropical environment, Weak rocks.

1 INTRODUCTION

The mine is localised in the northeast of a region known as Quadrilátero Ferrífero, a mineral-rich zone situated in the southeast of Brazil where the rainy season is well established over four months with cumulative precipitation over two thousand millimetres. The first reports of mineral exploration in the mine date back to the 18th century (around 1745) as a gold panning using enslaved labour. In the 19th century, gold production dramatically reduced to just a few grams, paralysing the mine for several decades. However, in the late 20th century, a mining company expanded a narrow ancient gold mine into a world-class iron ore open pit. It operated until 2015, when the mine was declared closed and a legacy mine, about 350 Mt of iron ore had been extracted from the mine in this period.

1.1 Timeline

In this mine, iron ore production was a big challenge for mine operators, especially during the first years, because of the continuous open pit geometry expansion, groundwater management and control of the security level of the overall slope. In the early 21st century, a substantial geotechnical program was performed to support the operational geotechnical team to elaborate the initial design criteria to assess and design the future expansions of the e open pit. However, when the open pit reached over 150 metres in 2006, at the north wall, the first signals of instabilities were noted, mainly by cracks and settlements on the main haul road.

In response to these events, in the following years were developed a geological-geotechnical campaign to investigate possible triggers and causes, it helps to design a new drainage system and maintaining of the old ones. In addition, a director plan and a detailed design of hydraulic elements (e.g., stepped chute), the mine operator deployed routine maintenance services. Finally, in the following years, studies focused on hydrogeological aspects were performed to improve a better understanding of the role of groundwater under the north wall behaviour and, mainly, its safety.

In the later years of mining, a sequence of basic designs was developed to propose effective remediation for active instabilities placed in the lower and upper portions of the north wall. As a result, action plans, monitoring specifications (before-during-after earthworks), quantitative risk assessment and geotechnical hazard map were established. Finally, according to the miner operator's policies, a design review task was carried out in 2021 to assess the proposed remediation of the north wall. The basic design produced in 2016 shows the most exhaustive concept from an engineering point of view. This will be the focus of the present paper.

1.2 Geological Context

In general, the open pit elongates in the EW direction and is located in an EW dipping south subvertical ductile shear zone on the north face of the Gandarela Syncline. The local geology presents the stratigraphic units constituted by schists from the Nova Lima group, quartzites from Moeda formation, phyllites from Batatal formation, hematite and itabirites from Cauê formation, dolomitic rocks from Gandarela formation and phyllites from Cercadinho formation covered by tertiary soil, and cut by metabasic intrusive rocks. According to Stacey (2018), in a simplified way, all these rocks are highly weathered, while quartzites show a lower degree of alteration. Besides, Innocentini (2003) comments that two shear zones are known in the open pit, one defined by the tectonic contact between the Nova Lima group and the Moeda formation (ENE-WSW direction dipping south) and another one represented by the contact between the Batatal phyllites and the iron formation defined as Transitional Unit and the iron formation (E-W direction dipping south). Then, the association among these several geological features and hydrogeological aspects has a considerable control on the stability behaviour of the north wall.

1.3 Geotechnical Monitoring

Across the years of mining activities, several geotechnical instruments were employed for geotechnical monitoring of the north wall, where they were composed of ground-based radar (GBR, 01 unit), robotic total station (RTS, 01 unit), 35 optical prisms, Casagrande piezometers (PZ, 37 units) and water level indicator (INA, 02 units). However, due to the lack of subsurface displacement, there is a limited understanding of the failure mechanisms in depth. Nevertheless, the monitoring data indicated that the groundwater fluctuation was directly influenced by the rainy seasons beyond pinched water in different lithologies. Additionally, the displacements in the north wall were induced by mining operations and controlled by the shear zones. In conformity with those interpretations, the basic design elaborated in 2016 addressed solutions to stabilise the wall.

2 2021 DESIGN REVIEW

The basic design, developed in 2016, concentrated efforts on assessing the condition of all open pit walls, where early work demonstrated that the north wall held safety conditions below the minimum acceptance criteria. Thus, in 2018, the pumping system (majorly by wells and secondarily by horizontal drain holes) was shut down, resulting in a progressive groundwater level rising and the lake infilling into the open pit. Figure 1 shows the consequence of that decision made associated with the absence of any remediation proposed by 2016 Basic Design, i.e., physical degradation of the north wall, two massive failures (called primary and secondary), erosion processes, loss of drainage elements and a dramatical reduction of the north wall safety conditions. Then, the design review in 2021 evaluated if the remediation proposals from the 2016 Basic Design are still applicable to the current open pit conditions.

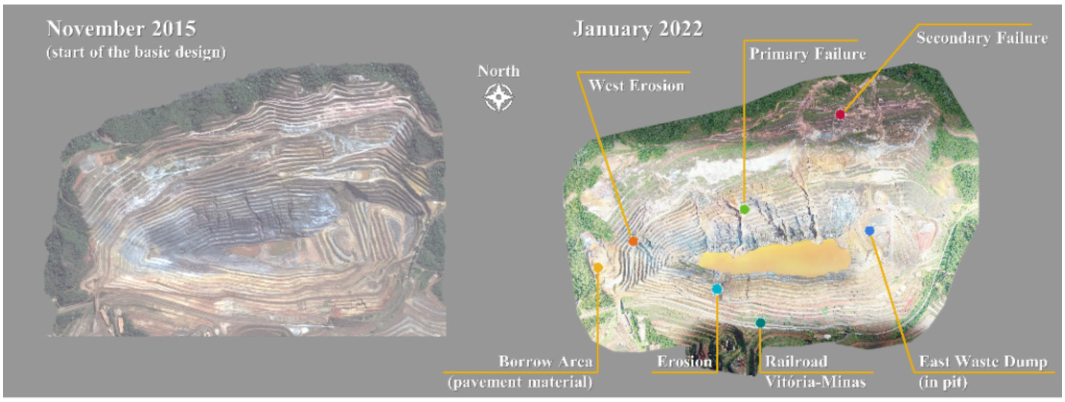

Figure 1. Open pit view in November 2015 (start of the basic design) and January 2016 (no works deployed).

2.1 2016 Basic Design

The 2016 Basic Design intended to evaluate the condition of the slopes at the time, on the way to propose technical solutions to increase the factors of safety (FoS) of the north wall, reducing or even eliminating mass movements (Table 1), and establish an efficient drainage system to control rainwater during the rainy season. For this proposal, three conceptual scenarios were studied as follows:

- Scenario 1: 2015 situation without any interventions on the north wall;
- Scenario 2: Geometric recovery of the upper portion of the north wall and infill the open pit with tailings;
- Scenario 3: Pushback of the upper portion of the north wall, buttress placement on the lower portion of the north wall, and subsequent lake infill.

Due to Scenario 2 needing further studies related to tailings behaviour and its influence on the local hydrogeology, Scenario 3 was selected and developed as the 2016 Basic Design (Figure 2). Both solutions delivered similar results about FoS, probability of failure (PoF), and risk management.

Table 1. General design criterion considered to elaborate the 2016 Basic Design.

Item	Design Criterion
Factor of safety (FoS)	An overall FoS corresponds to 1.30, but a local FoS equals 1.25/ it is acceptable for the middle portion of the north wall (due to uncertainty in geotechnical parameters).
Probability of failure (PoF)	An overall PoF equals 2.E-3 with limited access to the pit (Wesseloo & Read, 2009), but a local PoF equals 3.E-3 for the middle and lower portion of the north wall.
Geotechnical parameters	Adopted from laboratory tests (FURNAS, 2002); Consultants' reports; and Master theses from Innocentini (2003) and Alvares (2004).
Groundwater	Based on the hydrogeological model available, whose data are more assertive on the iron formation (PZ and INAs measuring were insufficient for the host rocks).

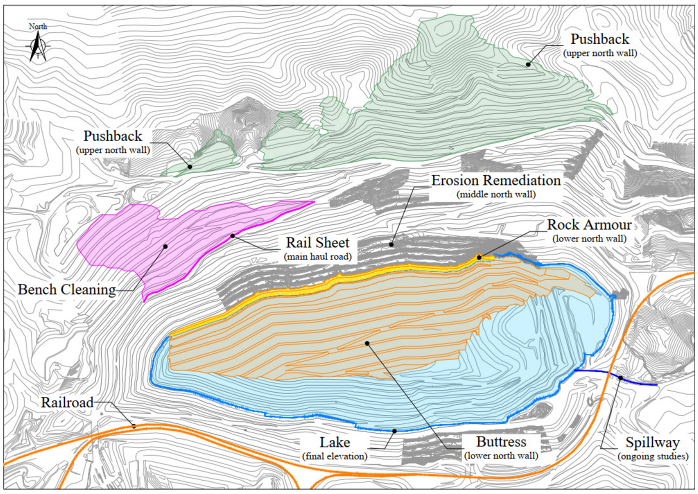

Figure 2. Remediation works proposal by the 2016 basic design (Pimenta de Ávila, 2016).

2.2 Assessment of the 2016 Basic Design

2.2.1 Impacts of the Latest Years on the Integrity of the Open Pit

The general geometry/topography of the north wall was severely impacted in the latest years by intense rainy seasons, especially in the 2019/2020 term when it reached 1,878 mm and widely overcame the mean annual rainfall of 1,350mm by approximately 40%. Additionally, the groundwater recovery accelerated, resulting in the north wall pressurisation and the formation of multiple seepages in different lithologies. It contributed to the primary failure (approx. 6 million m^3) at the end of 2019 and promoted the acceleration of the displacements on the secondary failure (approx. 2.5 million m^3). Another point that should be emphasised is the volume of sediments transported to the bottom of the open pit from various erosional processes (approx. 2 million m^3).

In financial terms, the total cost to recover the open pit is challenging due to yearly changes in the open pit geometry. In the same way, the increment of secondary failure deformation and erosions makes drainage elements impossible to be built because of loss of access and slope geometry. However, the total cost estimate indicates that the current cost is more than eighteen times the value predicted in the 2016 Basic Design.

2.2.2 Hydrogeological Model

Until 2016, when the basic design was elaborated, the available hydrogeological models aimed to attend to the dewatering for mining plan. They did not consider slope depressurisation or mitigate the driving forces responsible for the primary and secondary failures. However, a local hydrogeological model was elaborated in 2019, to understand the north wall`s hydrodynamic characteristics better, providing essential information for slope stability depressurisation assessments. This model intended to represent the interaction between the groundwater and the surface water, i.e., interpret the lake infill behaviour, the pressures inside the north wall and identify water flow directions for each geological formation (inclusive values).

In 2021, the 2019 hydrogeological model was revised, adopting the groundwater levels higher than considered in 2016 for schists and quartzites (above 1,000 m). This assumption directly impacts the global FoS of the upper portion of the north wall.

2.2.3 Statistical Variability

According to Maia (2007), in Geotechnical Engineering, it is recognized that geological features, such as discontinuities, faults and folding, influence the properties and behaviour of the rock mass. As a result, the bearing capacity of the rock mass is significantly affected, as well as its safety condition. In this sense, the 2021 Design Review verified insufficient data information for properly determining statistical parameters, and they were estimated with a simplistic approach. Based on the material types, the coefficients of variation (COV) were adopted depending on the type of material, quite different from the 2016 Basic Design, where a unique COV was considered regardless of the grain size fraction of material even though it is known that the statistical distribution function depends on material grain size classification and its plasticity (Baecher & Christian, 2003).

Adjustments were proposed for the geotechnical sections of the 2016 Basic Design based on the drillings campaign carried out in 2020, i.e., modifying geological contacts and the geomechanical classes in several materials. Regardless of not being expressive changes, they can be considered as a refinement of the information available for the development of the 2016 Basic Design.

Thus, the standard deviation was computed for the lithologies present in the north wall that drive the safety condition of that wall, where twice the standard deviation was adopted as the upper and lower limits. However, two adjustments were necessary, i.e., cohesion equals zero for its lower limit, and internal friction angle equals 42° for its maximum upper limit.

2.2.4 New Algorithm to Search Critical Slip Surface

Slide2 v. 9.0 computer code was used in the 2021 Design Review for limit-equilibrium analyses and its new numerical tool, Particle Swarm Optimization, unavailable in 2016, was used to investigate the critical non-circular slip surface. It allows obtaining the value of a variable in space that returns the minimum value of a given function whose response is dependent on that variable.

2.3 Limit Equilibrium Method (LEM)

The Limit Equilibrium analyses were used to investigate the potential slip surfaces in the upper portion of the north wall, more precisely above the primary failure. On this assumption, the analyses did not search the slip surfaces that progressed through the buttress. Two single cross-sections were used for LEM analyses to assess FoS surrounding primary and secondary failures.

From a deterministic approach, it was observed that the modifications on the upper portion of the buttress should be considered to increase FoS in the upper portion of the north wall. However, despite all efforts to improve the buttress arrangement, the increment gained in FoS was insufficient to supersede 1.30. Therefore, the analysis under pseudo-static loading calculated a minimum FoS of about 1.14 (global) and 1.09 (local).

Regarding the probabilistic approach, the PoF under static loading resulted in about 20% (local and global analysis), in all assessed scenarios. Nevertheless, for high lake depths (above 60 m) associated with pseudo-static loading, several potential slip surfaces showed PoF around 100%.

The results demonstrated that only the buttress adjustments are insufficient to promote and maintain adequate safe conditions. Then, a more widely remediation project should be developed to grant an elevated FoS following best practices from the mine operator and government, support a consistent reduction of the PoF and effectively deliver an efficient and sustainable treatment to the north wall.

2.4 Finite Element Method (FEM)

RS2 v. 9.0 computer code was used in the 2021 Design Review to evaluate the displacements and deformations of the north wall, the induced stresses, the loading stages where the effective stresses and deformations occur, the plastic zones extension, and finally, the degree of deformations.

The analyses performed in the 2021 Design Review presented results and behaviour trends close to the slip surfaces from the LEM analysis performed in the 2016 Basic Design, evident from the evaluation of the stress trajectories in different points and materials in the north wall cross-section.

It was noted that the lower portion of the north wall (primary failure) shows more critical failures and displacements than the upper portion. The instability occurred during the period when, after having already reached the final bottom pit, the pumping system was shut down, which contributed to the lake formation. It was evidenced in movements increment during this period.

Regarding secondary failure, the first stages of excavation showed conditions that were very close to the stability limit. The numerical results indicated that the lower portion of the north wall had expressive displacements and a concentration of shear components, although more minor, but in a large area without necessarily an unstable surface deployed. Those are also according to the displacement data evaluated from the orbital monitoring record (InSAR) shown in Figure 3.

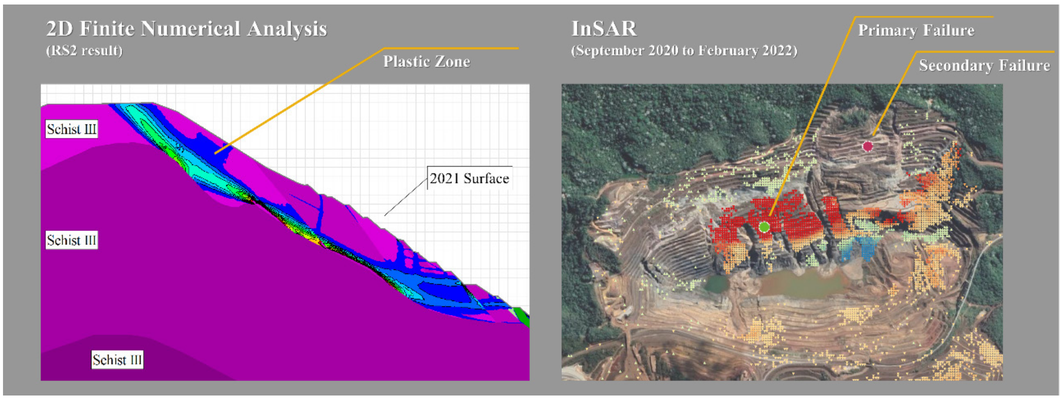

Figure 3. Computed slip surface in the secondary failure area and the displacements reported by InSAR.

3 CONCLUSIONS

The remediation proposed by the 2016 Basic Design could no longer address effective treatments for the decommissioning design of the open pit. However, the remediation actions, such as pushback in the upper portion of the north wall, a buttress in the lower portion of the same wall, and an entire depressurisation of the north wall, are still valid. The main reason for the inapplicability of the 2016 Basic Design is the massive displacements that occurred in the north wall, which are well noted through primary and secondary massive failures. Nowadays, the enormous volume of sediments inside the lake (over 2 million m^3) located at the toe of the primary failure made the earthworks to place the buttress more challenging. Additionally, the lack of access and slope geometry represents an extra challenge in terms of safety and the volume of material to be removed to reach the appropriate FoS.

REFERENCES

Alvares, R.A. (2004). Probabilistic Analyses for the Open Pit Design of an Iron Ore Mine (in Portuguese). Master thesis, Federal University of Ouro Preto, Ouro Preto, MG, Brazil, 121 p.

Baecher, G.B. & Christian, J.T. (2003). Reliability and Statistics in Geotechnical Engineering. John Wiley & Sons, New York, NY, USA, 618p.

FURNAS (2002). Geotechnical Tests, Triaxial Compression Tests and Direct Shear Tests (in Portuguese). Technical Report DCT.T.04.040.2002-R0, FURNAS CENTRAIS ELÉTRICAS S.A., Aparecida de Goiânia, GO, Brazil, 329 p.

Innocentini, M.D. (2003). Geomechanical and Hydrogeological Modelling and Stability Assessment of an Iron Ore Mine in Brazil (in Portuguese). Master thesis, Federal University of Ouro Preto, Ouro Preto, MG, Brazil, 168 p.

Maia, J.A.C. (2007). Probabilistic Modelling of the Plastic Zone of Underground Excavations in Rock Masses (in Portuguese). PhD Thesis, Publishing G.TD-040/07, Departamento de Engenharia Civil e Ambiental, University of Brasília, Brasília, DF, 161 p.

Pimenta de Ávila (2016). Basic Design: Risk Assessment of an Open Pit in Brazil (in Portuguese). Technical Report RL-1000DD-X-15654, Pimenta de Ávila Consultoria Ltd., Nova Lima, MG, Brazil, 80 p.

Stacey, P. (2008). Review of Pit Slopes Stability at the DIFS Operations. Technical Report DIFS LR 01-08, Stacey Mining Geotechnical Ltd., Vancouver, CBC, Canada, 25 p.

Wesseloo, J. & Read, J. (2009). Acceptance Criteria. Guidelines for Open Pit Slope Design, J. Read and P. Stacey (eds.), CSIRO Publishing, Melbourne, Australia, 221-236.