Three-Dimensional Stability Analysis in an Open-Pit Iron-Ore Mine

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This project was developed in an iron-ore open-pit mine located in Brazil, which exhibits outcrops of friable rock units with a high contrast in rock stiffness between the different rock units of the deposit and a presence of a shear band in between units. Therefore, this study was aimed at understanding the failure mechanisms acting on the slopes. Considering the background information and the characteristics of the rock units at the site, *FLAC3D* was chosen as the best tool to correctly represent this problem. The study was based on three specific stages: 1) compilation and review of the geological, geotechnical, and structural information of the site; 2) a calibration stage based on reproducing to the best possible extent three documented instabilities; and 3) a predictive stage for the stability conditions of the slopes in future design (final pit), plus interramp angle (IRA) recommendations.

Project Background

An iron-ore open-pit mine located in Brazil has experienced several documented instabilities. These events have been distributed in almost all slopes of the mine, inducing failure events that range from a single bench scale up to bench stacks 150 m high. Most of these failure events correspond to circular failures, which have occurred in different time scales, but each of these have been responsible for halting operations in the local areas of failure. In this context, it is critical to assess the stability condition of future mining and analyze if the interramp slope angles (IRAs) being used are well suited for the rock mass units present in the deposit.

This study aims to understand the failure mechanisms acting on the mine slopes in order to perform a reliable predictive three-dimensional geotechnical stability analysis and obtain recommendations on the design slope angles.

To accomplish the objective of the study, this project was planned in terms of three stages of work:

1. Initial stage based on a process of compilation and review of the data.
2. Calibration stage based on reproducing to the best possible extent three instabilities recorded and documented in slopes of the mine.
3. Predictive stage for the stability conditions of the slopes in one future design (Final Pit) along with interramp angle (IRA) recommendations.

Geology of the Deposit

This deposit exhibits 11 lithologies ranging from friable rock units (which are extremely weak rocks) to competent rock units. The contrast between friable and competent rocks is evident not only in the strength properties, but also by a high contrast in rock stiffness.

The main feature identified in the rock units, with special importance in the friable rock units, is the presence of foliation and bedding planes. In some parts of the mine, the orientation of these planes is unfavorable to the slope design.

As an iron-ore deposit, the ferrous formation is delimited from a mafic formation by a shear band that exhibits significantly low strength parameters and has been a contributor to instabilities whenever it daylights in the slope.

Strength Parameters of the Materials in the Deposit

The properties of the materials in the deposit are shown in Table 1.

Table 1Material Properties

Rock Unit	Dry Density (kg/m^3)	Sat. Density (kg/m^3)	Coh. (kPa)	Fric. Angle (°)	E_{RM} (MPa)	v
MS	2900	2900	3200	50	29658	0.22
MSD	3000	3000	185	26	6405	0.25
MD	1850	2000	72	21	426	0.30
HF	3700	3800	95	31	1050	0.28
HC	3700	3700	250	45	29658	0.22
JP	3700	3700	3750	48	29658	0.22
CG	3000	3000	65	43	200	0.35
CQ	3000	3000	65	43	200	0.35
AT	2000	2000	19	27	20	0.35
ZC	1900	2000	7	14	200	0.35
Joints (HF / MD)	N/A	N/A	13	18	N/A	N/A
Joints (Rest)	N/A	N/A	18	25	N/A	N/A
Faults	N/A	N/A	0	20	N/A	N/A

Selection of Constitutive Models

Due to the geological set of the mine deposit, the following approach was adopted:

- Friable rock units with strong features in terms of beddings or foliations were represented by an elasto-plastic model with a Mohr-Coulomb failure envelope and ubiquitous joint anisotropy.
- Friable rock units without structure presence and competent rock units were represented by a standard elasto-plastic model with a Mohr-Coulomb failure envelope.

Methodology

The overall methodology is presented in this section, along with the description of the models used in each stage of the project.

Calibration of Documented Instabilities

For each model (representing each documented instability), the iteration process started with the mean value of each property for each rock unit (provided by the Client). As the calibration process progressed, the values were updated keeping their magnitudes within the measured range according to the test data.

The process was complete when a set of calibrated rock parameters that reproduces both the documented instabilities and the current pit behavior was found. The analysis of the current pit including testing the calibrated parameters to assess how well they reproduce the actual conditions of the current pit.

Predictive Analysis and Interramp Angle (IRA) Recommendations

The outcome of the predictive analysis is the assessment of the stability conditions of the Final Pit based on the calibrated properties. This is achieved through the calculation of Factor of Safety (FoS) using the Shear Strength Reduction (SSR) technique. Also, recommendations of the IRA are provided.

Calibration Results

This section shows the results of simulating each instability using the final set of calibrated parameters.

Instability 1

As shown in Figure 1, the model shows a reasonable correlation with the documented instability. Although the model overpredicts the northmost extension of the documented failure, the extensions to the south, in the east-west axis, and in vertical are reasonable.

In Section BB' (N = 1440), a failure surface is observed that encompasses level 485 to 620 (failure height of 135 m), reaching a failure depth of 33 m, which is considered reasonable compared to the maximum height of the failure reported by the mine (105 m).

It is relevant to notice the role of the shear band in controlling the failure extension. Because of the lower strength of this shear band, it becomes a preferential failure surface, controlling the stability of this area.

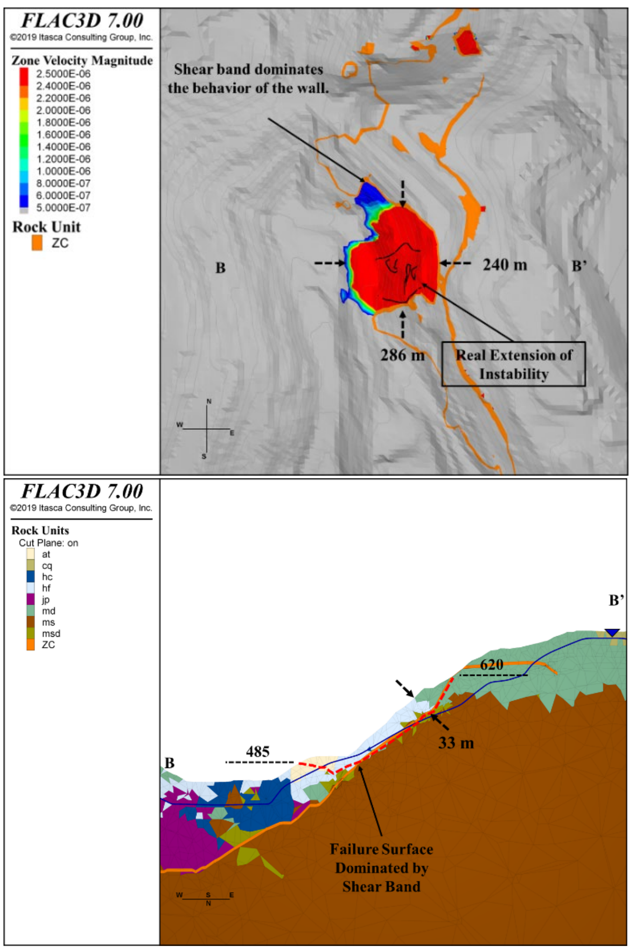

Figure 1 Top: Calibration of Instability 1 in plan view and BB' section location. Bottom: Cross-section of BB'.

Instability 2

Instability 2 could not be reproduced (Figure 2). After several attempts, it was concluded that more factors need to be added to the model to represent the observed behavior.

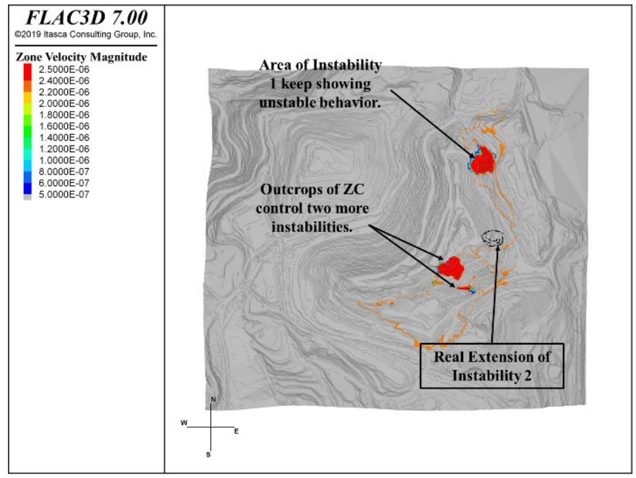

Figure 2 Unsuccessful calibration of Instability 2 (plan view).

Instability 3

For the calibration of Instability 3, the phreatic level was arbitrarily raised to 20 m below the surface of the pit. This was done to reproduce the saturation conditions reported in the documented instability. This approach is aimed at representing the reported lack of proper dewatering in the area where the instability occurred, but unfortunately also over-estimates the influence of water outside the failed area.

As shown in Figure 3, the model shows a fair correlation with the documented instability. When comparing the model prediction against the documented failure contour, it is necessary to emphasize the following:

- The model reproduces reasonably well the extent of the failure in the north and west slopes.
- The model over-predicts the extension of the failure surface to south, mainly due to the

over-estimation of saturation, and due to the presence of the shear band to the southeast.

In Section DD’ (N = 310), the model exhibits a failure surface that involves level 415 to 665 (failure height of 250 m), reaching a failure depth of 100 m. When compared to the reported failure, which reached a maximum height of 150 m, the model provides a reasonable result considering the assumption of raising the phreatic level.

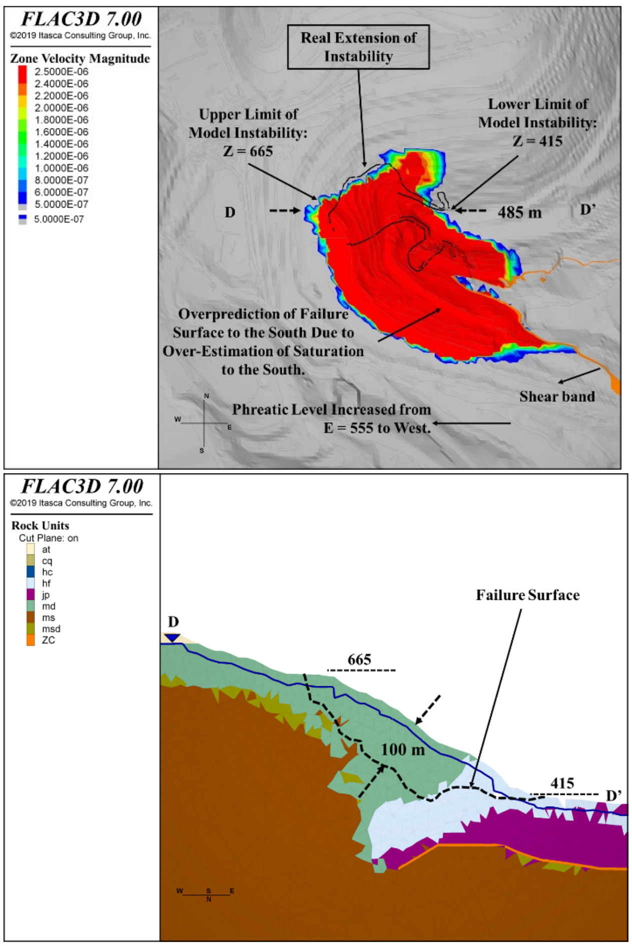

Figure 3 Top: Calibration of Instability 2 in plan view and DD’ section location. Bottom: Cross-section of DD’.

Predictive Analysis

Predictive analysis was divided into two branches:

- The first was aimed at assessing the stability condition of the Final Pit by characterizing the rock mass with the set of calibrated parameters. To achieve this goal, FoS was calculated using the SSR technique.
- The second was intended to advise the mine with IRA recommendations for each rock unit in terms of the calibrated parameters found.

Factors of Safety for Final Pit

The FoS contours are shown in Figure 3.

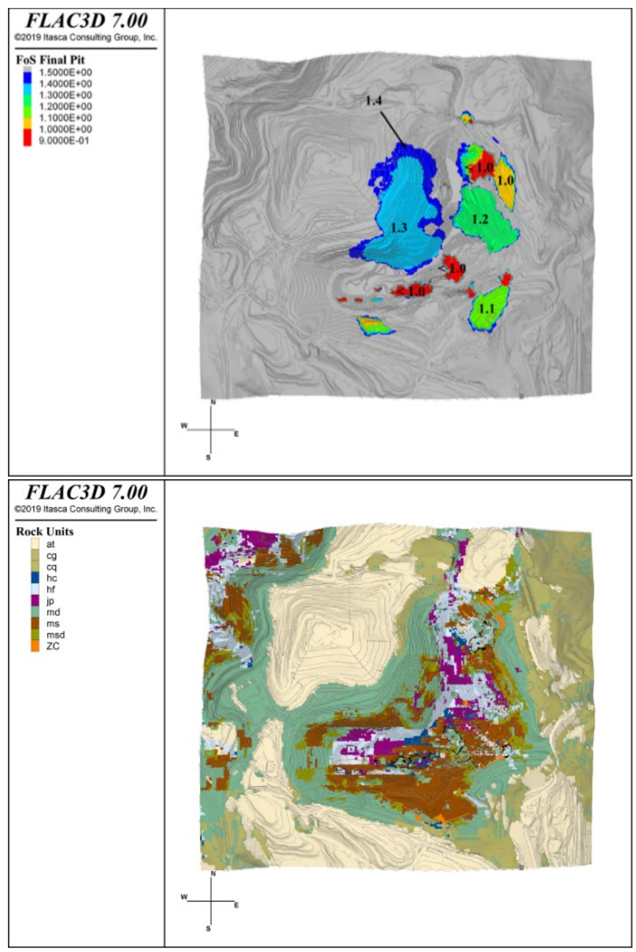

Figure 4 Top: FoS contours for final pit in plan view. Bottom: Rock units for final pit in plan view.

According to the previous figure, the slopes of the Final Pit exhibit the following:

- FoS ≤ 1.1 where the shear band configures geometry of a "Planar Failure" with a small rock bridge or daylighting at the slope.
- 1.1 ≤ FoS ≤ 1.3 where the shear band configures geometry of a "Planar Failure" where the rock bridge is wide enough to hold the failure but could induce relevant deformations in the form of cracking.
- FoS ≥ 1.3 in rock masses where the failure is expected through the matrix (Circular Failure) and/or promoted by the joints.

All the points stated above highlight the importance of correct determination of the shear unit in this deposit.

IRA Recommendations

The IRA recommendations were developed using a simplified two-dimensional *FLAC/Slope* v8.0 analysis considering the following:

- The analyses were carried out in dry conditions. This must be considered carefully, because the phreatic levels have proven to be a critical contributor to instabilities.
- The acceptability criterion was FoS ≥ 1.3.
- The rock units in the mine were assessed using only the rock matrix without any faulting or joint sets.
- Due to the importance of joint sets in the HF and MD behavior, according to the results shown previously, the IRAs of the most unfavorable orientations per joint set that could be found in the model were also assessed.

The design charts with and without joints are shown in Figure 4.

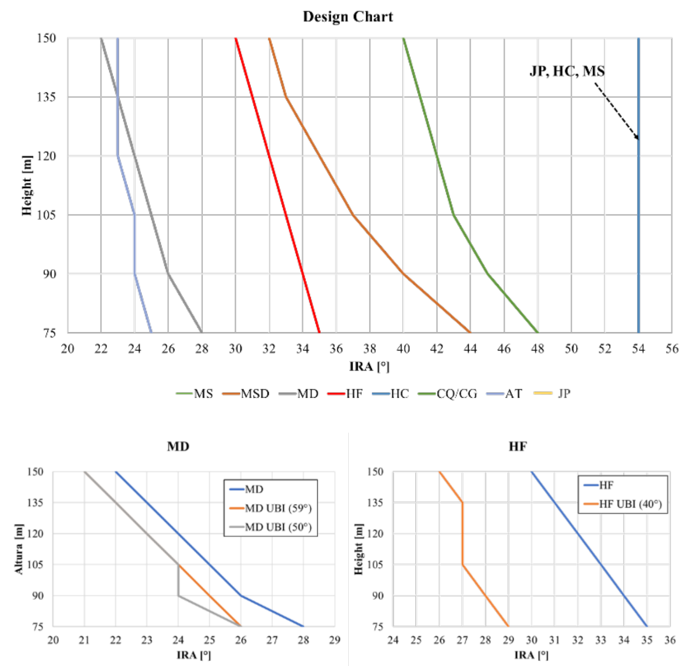

Figure 5 IRA recommendations.

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