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Calibration of a Three-dimensional slope stability evaluation in Brazilian iron open pit mine

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ABSTRACT

It has historically been frequent among geotechnical practitioners, that the stability analysis of the slopes of an open pit is performed using a two dimensional section representing the highest and steepest walls within a certain geological setting. However, the literature shows that to predict rupture events in an open pit, a three-dimensional analysis would better represent the actual conditions, as the spatial distribution of the lithology and the structural features play an important role when defining the stability of the slopes. This paper presents the case study of an open it located in Brazil, which experienced instabilities between the years 2001-2019. An evaluation of the behavior of the open pit was performed by calibrating the strength parameters to represent the best documented rupture events. The three-dimensional model was made using the FLAC3D software. The results show that there is a good correlation between the results of the model and the reports of past instabilities. Finally, recommendations are presented for the

inter-ramp angles for each lithology based on the calibrated stability analyzes performed. This work seeks to contribute to the knowledge in evaluation techniques for the three-dimensional behavior of open pits.

Key words: open-pit, slope stability, calibration, three-dimensional analyses, case study.

DECLARATIONS

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

The data that support the findings of this study are available from Vale S.A. but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Vale S.A.

Code availability

Not applicable.

Authors' contributions

Vidal Félix Navarro Torres

Performed the analysis, contributed data and conceived the analysis.

Rodrigo Dockendorff

Performed the analysis, analysis tools and designed the analysis.

Juan Manuel Girao Sotomayor

Performed the analysis, analysis tools, wrote the paper.

Cristian Castro

Performed the analysis, analysis tools.

53 Aristotelina Ferreira Silva

54 Performed the analysis, collected data.

55 **Ethics approval**

56 Not applicable.

57 **Consent to participate**

58 Informed consent was obtained from all individual participants included in the study.

59 **Consent to publication**

60 The participant has consented to the submission of the case report to the journal.

1 INTRODUCTION

2 Commonly, to guarantee an economically profitable while safe mining operation, the
3 stability of the open-pit slopes has been assessed using two-dimensional analyzes that are
4 usually more conservative than a three-dimensional analysis (Lam e Fredlund, 1993;
5 Albataineh, 2006; Li et al., 2009; Michalowski, 2010; Li et al., 2010; Akhtar, 2011; Wines,
6 2016; Azizi et al., 2018).

7 A two-dimensional analysis in limit equilibrium does not take into account the strength
8 generated on the axis parallel to the length of the slope, an effect that does exist in 3D analysis
9 (Lefebvre et al., 1973; Baligh e Azzouz, 1975; Leshchinsky e Baker, 1986; Saeed et al., 2015;
10 Chakraborty e Goswami, 2018; Zebarjadi et al., 2018).

11 The application of three-dimensional numerical analysis for open-pits is more appropriate
12 because it can take into account several key factors, such as: topography, hydrogeological
13 conditions, in situ stress, among others, with significant differences compared with two-
14 dimensional analyses (Griffiths e Marquez, 2007; Shen e Karakus, 2013; Wines, 2016), this is
15 very important for mining activities because responsible mining seeks to ensure maximum
16 recovery of the ore without affecting safety, which can have a significant positive economic
17 effect to the mine (Hoek e Bray, 1981; Ali e Morteza, 2014; Zevgolis et al., 2018).

18 This case study aims to understand the failure mechanisms acting on open-pit slopes in
19 an iron mine located in Brazil (Figure 1), using a calibrated three-dimensional model in finite
20 difference software FLAC3D (Itasca, 2011).

21 CASE DESCRIPTION

22 The study area has experienced fourteen documented instabilities throughout its
23 existence, these events have been distributed in almost all slopes of the mine. The main features
24 of the events were a response to mining advance, the appearance of cracks after the interruption
25 of operations, occurrence of local landslides and ruptures due to geological conditions. The
26 events took place in different periods and had different scales as shown in Table 1.

27 Consequently, it is necessary to calibrate the rupture events that occurred to improve the
28 confidence in predicting the future behavior under design geometries.

29 The main geological structures present are deformations-bands, shear zones and families
30 of joints and faults. The deformation-bands were verified basically in the iron formation and
31 have variable orientations, usually with signs of shear. The surface of the deformations-bands
32 is sinuous and anastomosed, probably related to shear. The shear planes are generally parallel
33 to the deformation-band of the iron formations and also show high scatter. A shear zone (ZC)
34 occurs in the contact between Ferriferous and Mafic formations, this zone exhibits a high
35 mechanical weathering and low strength. The joints show relatively small persistence and they
36 are found open, filled with talc or carbonate, or closed. Transcurrent faults occur in the mine,
37 orthogonal to sub-orthogonal to shear (in mafic rocks). The main direction of the occurring
38 faults is NW-SE.

39 A review of the events reported in Table 1 was carried out, finding that the most
40 representative instabilities in the open pit correspond to the years 2013, 2017 and 2019 (Figure
41 1), therefore these will be the events used for the calibration process.

42 The three-dimensional model used the pre-mining topography to represent the initial in
43 situ stress state, then the open pit geometries were evaluated for the above mentioned failure
44 events plus the current condition. The geological block models developed by the mine were
45 used to determine the spatial distribution of the lithology. The failure events used for calibration
46 are detailed below.

47 The 2013 instability occurred in the East Slope of the main pit, near the access ramp. The
48 failure surface involved 7 benches, reaching a maximum height of failure of 105 m (Figure 2).
49 This failure mechanism initially was related to a circular failure with contribution of structural
50 control. After 2013, no significant signs of mass movement have been observed in the area.

51 The 2017 instability occurred in the Upper Part of the East Slope of the main pit, below
52 the main access ramp. The failure surface involved 4 benches, reaching a maximum height of

failure of 60 m (Figure 3). Initially this failure mechanism was related to a combined planar-circular failure, involving as contributing factor the presence of a weak contact between Ferriferous Formation and Metabasic Formation.

The 2019 instability occurred in the South-West Slope of the main pit. The failure surface involved 10 benches, reaching a maximum height of failure of 150 m (Figure 4). Initially, this failure mechanism was related to a circular failure, and the instability was due to locally insufficient dewatering and erosional process.

MONITORING

The rupture events that occurred in 2013, 2017 and 2019 in the open pit were monitored using instruments installed in these areas, including prism networks, ground radar, piezometers and water level indicators. Daily rainfall data were also used to analyze these events. The precision and periodicity (24/7) of radar monitoring (SSRXT - GroundProbe) enabled more robust and rapid analyses of the displacements occurring in the study areas. The further verification of the beginnings of the accelerations and their progression to rupture was thus possible. This type of monitoring was more effective than other types mainly due to the speed with which the events occurred, and the results helped with risk management and the decision to block the areas.

2013 (03/07/2013) - The accelerations began 24 h before the event, with a greater peak rupture displacement of 250 mm.

2017 (03/12/2017) - The accelerations began 24 h before the event, with a greater peak rupture displacement of 140 mm.

2019 - (04/01/2019) - The accelerations began 2 days before the event, with a greater peak rupture displacement of 640 mm.

Monitoring by prisms was concentrated in the area of the ruptures that occurred in 2013 and 2017; however, as it was a conventional survey with periodic readings every two weeks, the analyses were slower and showed indications of progression.

79 2013 - Two prisms showed relevant movements in the 3 axes, ranging from 25 mm-90 mm on
80 the X and Y axes and reaching 50 mm on the Z axis.

81 2017 - The prism that best represented the event showed a displacement of 172 mm in the XY
82 direction and a displacement of 35 mm in the Z direction, with a maximum displacement rate
83 of 2.9 mm/day. This fact was confirmed by the greater opening of the established crack and the
84 settlement of the area.

85 Monitoring was achieved with piezometers and water level indicators established along the pit,
86 and the readings prior to the events showed that some of the instruments presented small
87 increases in the water table level, even considering the amount of rainfall that occurred in the
88 period, because the recharge time in the massif is longer.

89 The rainfall monitoring data show that rainfall events played a role in the events that occurred,
90 as described below:

91 2013 – Cumulative rainfall from Jan/13 - March/07/13 of approximately 700 mm, and rainfall
92 occurred at least 3 days before the event.

93 2017 - Cumulative rainfall from Jan/17 - March/12/17 of 717.90 mm, and 72 mm of rainfall
94 occurred 1 day before the event.

95 2019 - Cumulative rainfall from Jan/19 - Apr/01/19 of 543.51 mm, and 23.8 mm of rainfall
96 occurred 1 day before the event.

97 **ROCK MASS PROPERTIES**

98 A database of laboratory tests in different lithologies was available at the site to determine
99 the strength parameters. The lithologies with the greatest participation in the instabilities
100 correspond to the friable hematite (HF) and decomposed mafic (MD) formations. A total of 38
101 data points for friable hematite (HF) and 102 data points for decomposed mafic (MD) were
102 used to define the range and variability for the statistical distribution used in the three
103 calibration events. The distribution of the parameters with the most influence on instabilities is
104 shown in Table 2.

A summary of the strength parameters of all lithologies is shown in Table 3 including the shear zone (ZC) mentioned above.

CALIBRATION AND VALIDATION PROCESS

In FLAC3D, the numerical velocity contours are used as a proxy to interpret stability conditions. These velocities are given without units, because they are mathematical artifacts and only represent the convergence of the numerical solution. It is Itasca's experience that numerical velocities greater than $2.5e^{-6}$ after a significant number of timesteps are an indication of unstable behavior, although this reference value needs to be validated on a case-by-case basis.

The calibration process identified the HF, MD and ZC rock units as the main units that control the documented instabilities along with a structural anisotropy that was represented in the analysis using a ubiquitous joint constitutive model. The set of calibrated parameters can be seen in Table 4. The modeling results representing each rupture event calculated using the calibrated parameters are presented below.

2013 Calibrated Instability

The model shows a reasonable correlation with the documented 2013 instability (Figure 5). However, the model overpredicts the Northward extension of the documented failure, the extension to the South, in the East-West axis and in Vertical are reasonable. In Section BB' (Figure 6) we observe a failure surface that encompasses from level 485 to 620 (failure height of 135 m) reaching a failure depth of 33 m. When compared to the reported failure, which reached a maximum height of 105 m, the model is considered to be reasonable.

It is relevant to notice the role of the shear zone (ZC) in controlling the failure extension. Because of its lower strength, it becomes a referential failure surface, controlling the stability of this area. Due to the above, and by observing the 2013 pit in plan view, it can be noticed that two more areas exhibit unstable behavior (Figure 7). These areas are controlled by ZC, all of them showing the same geometry: Planar failure where the ZC is the failure surface.

2017 Calibrated Instability

The instability of 2017 could not be reproduced (Figure 8). After several attempts, it was concluded that more factors need to be added to the model in order to represent the observed behavior. The slope seems to exhibit the occurrence of sills that seem to control the occurrence of the instability. In the Ferrous Rocks, metabasic sills (more rigid rocks within more plastic rocks) occur in concordance with foliation, with widths that range from 0.5 m up to 3 m. The model could not interpret the occurrence of these sills, because of lack of information. Therefore, the calibration process in this area ended with unsuccessful results.

It is relevant to notice in Figure 8 that the area of reported instabilities of 2013 remains unstable in 2017. This is due to the fact that the slope does not exhibit a significant change in the overall geometry. Therefore, the slope maintains an unstable condition which does not agree with field observations.

2019 Calibrated Instability

For the calibration of 2019, the phreatic level was arbitrarily raised up to 20 m below the surface of the pit. This was done in order 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 elsewhere outside the failed area. As shown in Figure 9, the model shows a fair correlation with the documented 2019 instability. When comparing the model prediction against to the documented failure contour, the model reproduces fairly well the extent of the failure in the North and West slopes. The model overpredicts the extension of the failure surface to South, mainly due to the over estimation of saturation and also due to the presence of ZC to the South East.

In Figure 10 the section DD' exhibits a failure surface that involves from 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 is considered to provide a reasonable yet conservative result considering the assumption of rising the phreatic level.

Validation of Calibrated Parameters (2019 current pit)

With the set of calibrated parameters, the 2019 current pit was evaluated as a means to validate the properties derived. To do so, velocity contours are shown in Figure 11 and Figure 12.

The calibrated set of parameters remain conservative. In Figure 11 it is observed that the area of 2013 instability remains unstable. This again is due to the small change in the geometry in this sector. While the 2013 area shows unstable behavior due to geometrical reasons, there are a few more areas of unstable behavior. In the South of the open pit, three areas exhibit unstable behavior, but again these areas are related to “planar failures” formed by the interpretation and daylighting of the ZC rock unit. Another area of unstable behavior locates at the toe of the West Slope (Figure 12). This region exhibits toppling at the toe. This toppling mechanism spreads upward the deformation in the lower part of the West Slope (Interramp Angle or IRA $\sim 37^\circ$). This could suggest conservative calibrated parameters, or changes in the joint orientations in this area which are not documented in the geotechnical model.

Nonetheless, due to the reasonable representation of the past instabilities and although conservative, it is deemed that the new set of parameters can be used to evaluate future design geometries of the open pit.

STABILITY ANALYSIS

The analysis was divided into three stages: (a) the first, aimed to assess the stability condition of the current pit (Figure 13), by characterizing the rock mass with the set of calibrated parameters and calculating Factors of Safety (FoS) using the Shear Strength Reduction (SSR) technique; (b) the second is intended to advice the mine with IRA recommendations for each rock unit, in terms of the calibrated parameters established ; (c) finally, the stability of a future open pit geometry is evaluated (Figure 14).

When comparing FoS contours for current and future pit, two behaviors can be noticed:

All the sectors with $FoS \leq 1.1$ remain "unstable", this is due to:

- Occurrence of unstable behavior of the area of 2013 instability, which remains with essentially no changes in its geometry.
- Geometries of "planar failure" controlled by ZC during this time period.

Due to mining of the future pit, two large sectors exhibit $1.2 \leq FoS \leq 1.3$. This occurs in the West Slope and in the East Slope.

- In the west, the slope shows a $FoS \geq 1.3$ due to the increase in the IRA. In this sector of the mine, the rock mass is characterized by MD unit, controlling the failure mainly through the rock matrix, because the joint sets dip -59° (Considering IRA-31-40°).

- In the East, the slope shows a $FoS \geq 1.2$ due to the role of ZC in forming a geometry of "planar failure" contained by a rock bridge composed mainly by HF unit. Most of the final pit shows an acceptable stability condition (i.e. $FoS \geq 1.3$).

IRA RECOMMENDATIONS

The IRA recommendations were developed using a simplified two-dimensional FLAC/Slope v8.0 analysis, considering that the analyses were carried out in dry conditions. This assumption must be considered carefully, because the phreatic levels have proven to be a critical contributor to instabilities in the open pit. The acceptability criteria was: $FoS \geq 1.3$.

For the rock units in the mine, they were assessed using only the rock matrix without any faulting or joint sets. This included: MS, MSD, MD, HC, HF, JP and CQ. Due to the importance of joint sets in the HF and MD behavior, according to the results shown previously, it was also assessed the IRAs including the most unfavorable orientations per each that could be found in the model. The joints were modeled with $c=13$ kPa and $\phi=18^\circ$. The design charts without and with joints are shown in Figure 15 and Figure 16.

CONCLUSIONS

The work describes the calibration process of a 3D stability model of an open pit located in Brazil. Three documented instabilities located in different areas of the open pit were used in the calibration process of the strength parameters for each lithology.

The calibration process identified the HF, MD and ZC rock units as the main units that control the documented instabilities along with ubiquitous joints.

As stated during the work, all the joints were treated the same in the numerical modeling. Although during the calibration process the joint sets that outcrop in HF and MD were treated differently, there were no documented differences between shear and bedding planes that could induce differences in the behavior of the slopes.

Finally, the model is considered acceptable, representing the current conditions of the open pit and as a result of the model, recommendations for interramp angle were made for each lithology for a future open pit geometry, taking into account the maximum material removal in a safe and economically profitable way.

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1 **TABLES**

2
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Table 1. History of ruptures

ID	Period	Sector	Failure mechanisms	Scale	Description
1	2001	South	No Data	No Data	Breaks due to the advance of mining
2	2002	South	Circular	No Data	Reactivation of cracks due to work stoppage
3	2002	South	Circular	No Data	Embankment movement with settlements at the top
4	2004	East	Circular	45 m	Slide
5	2005	South	Circular	No Data	Cracks in the slope face
6	2006	Central	Circular	75 m	Slide
7	2007	South	Circular	No Data	Slide
8	2008	Central	Circular	75 m	Slide
9	2009	South	Circular	75 m	Rupture associated with geological conditions
10	2010	South	Circular	45 m	Rupture associated with geological conditions
11	2013	East	Circular	105 m	Rupture associated with geological conditions
12	2017	East	Circular	60 m	Rupture associated with geological conditions
13	2019	South	Circular	120 m	Rupture associated with erosive process
14	2019	South	Circular	150 m	Rupture associated with erosive process

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Table 2. Data distribution parameters

Rock Unit	Cohesion (c', kPa)					Friction angle (ϕ' , °)				
	Min.	Max.	Mean	Median	SD	Min.	Max.	Mean	Median	SD
Decomposed mafic	0.0	219.0	65.2	35.1	62.2	13.7	41.1	29.5	30.0	5.6
Friable hematite	0.0	258.0	109.7	108.0	72.1	33.0	46.0	39.8	39.8	3.7

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Table 3. Summary of strength parameters

Rock Unit	ID	γ_{dry} (kN/m ³)	γ_{sat} (kN/m ³)	c' (kPa)	ϕ' (°)	JRC	JCS (kPa)	GSI	m_i	σ_c (MPa)
Fresh mafic	MS	29.0	29.0	3200	50	-	-	70	7	151
Semi decomposed mafic	MSD	30.0	30.0	240	32	-	-	60	3	14
Decomposed mafic	MD	18.5	20.0	*	*	-	-	50	2	0.8
Friable hematite	HF	37.0	38.0	*	*	-	-	-	-	-
Compacted hematite	HC	37.0	37.0	250	45	-	-	-	-	-
Jaspelite	JP	37.0	37.0	3750	48	-	-	70	7	167
Canga	CQ	30.0	30.0	65	43	-	-	-	-	-
Shear zone	ZC	19.0	20.0	9	18	8	240	-	-	-

* See Table 2.

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Table 4. Summary of Final Calibrated Properties

Rock Unit	ID	γ_{dry} (kN/m ³)	γ_{sat} (kN/m ³)	c' (kPa)	ϕ' (°)	E_{RM}	ν
Fresh mafic	MS	29.0	29.0	3200	50	29658	0.22
Semi decomposed mafic	MSD	30.0	30.0	185	26	6405	0.25
Decomposed mafic	MD	18.5	20.0	72	21	426	0.30
Friable hematite	HF	37.0	38.0	95	31	1050	0.28
Compacted hematite	HC	37.0	37.0	250	45	29658	0.22
Jaspelite	JP	37.0	37.0	3750	48	29658	0.22
Canga	CQ	30.0	30.0	65	43	200	0.35
Shear zone	ZC	19.0	20.0	7	14	200	0.35
Ubiquitous Joints (HF/MD)		N/A	N/A	13	18	N/A	N/A
Ubiquitous Joints (Rest.)		N/A	N/A	18	25	N/A	N/A
Faults		N/A	N/A	0	20	N/A	N/A

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Figures

Figure 1

Iron open pit and instabilities location

Figure 2

(a) Pre and (b) Post Failure Condition - East Slope (2013)

Figure 3

(a) Pre and (b) Post Failure Condition - East Slope (2017)

Figure 4

(a) Pre and (b) Post Failure Condition – South West Slope (2019)

Figure 5

Results of Calibration of 2013 Instability

Figure 6

Results in Section B-B' - Calibration of 2013 Instability

Figure 7

Effect of ZC - Calibration of 2013 Instability

Figure 8

Results of Calibration of 2017 Instability

Figure 9

Results of Calibration of 2019 Instability

Figure 10

Results in Section D-D' - Calibration of 2019 Instability

Figure 11

Velocity Contours - 2019 current Pit.

Figure 12

Velocity Contours in Section EE' - 2019 current Pit.

Figure 13

FoS current Pit

Figure 14

FoS Final Pit

Figure 15

Design Chart (without joint sets) for a FoS of 1.3 and under dry conditions. Fig.

Figure 16

Design Charts for MD and HF (with ubiquitous Joints), for a FoS of 1.3 and under dry conditions.