Diagnosis of bench stability conditions in an iron ore open pit in the Quadrilátero Ferrífero/Minas Gerais/Brazil

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ABSTRACT: The Quadrilátero Ferrífero, an important mineral province located in the state of Minas Gerais/Brazil, is influential for its world class deposits of commodities, such as iron ore. As in any other excavation, it is fundamental to grant the necessary bench slope stability conditions for the operation of its open pits. In this scenario, this paper develops products that supports the primary part of the diagnosis and planning of mining conditions in an iron mine. Field mapping and geological survey allowed gather structural data that supports geotechnical zoning of current slopes; kinematic analysis considering geometric conditions and the definition of potential types of failure mechanisms. This provided the overview of planar, wedge and flexural toppling occurrences in specific regions of the current operation. Corrective measures and geometric recommendations are discussed, as solution to ensure the stability of the structures and maintaining the production of this important commodity.

Keywords: Slope Stability, Bench Analysis, Types of Failure, Quadrilátero Ferrífero.

1 INTRODUCTION

In central of Minas Gerais, state of Brazil, the Quadrilátero Ferrífero area consist of a system of iron ridges where open pit mines have been developed since early 20th century. Its geological setting consists of Archean greenstone belt Rio das Velhas Supergroup and a Proterozoic metasedimentary sequence of Minas Supergroup, both severely folded over the Rhiacian and Brazilian events. Besides the structural complexity of this area, it is also remarkable that the weathering has played a very important role in the surface, controlling not only the geomorphological aspect, but also the mechanical behavior of the rocks found in the area, in a context with friable ores at depth due to the hydrothermal process (Rosiere & Chemale, 2013). Those reasons, both structural aspects and weather action over the itabirite layers have been used to explain the iron ore identified. These are also the reasons that makes the Quadrilátero Ferrífero so unique once its rock masses are adversely affected by.

Naturally, open pit iron ore operations must deal daily with the geological and geotechnical challenges found. One of these challenges relies on determining the adequate scale of analysis that better indicates a model of the failure mechanisms for the rock masses availed. Considering that, the correct assessment also orientates the best approach to identify, as well as mitigate any instability on the operational slopes.

In most cases, it is necessary to divide a bench scale analysis from an interramp or global scale. For the first, the structures found have a primary role in the possible failure. For a bigger scale, the rock mass tends to be the protagonist.

The objective of this work includes the survey, treatment and development of a product that will support the diagnosis and planning of the stability conditions of two iron ore mines. This paper synthesizes data to generate a diagnosis of stability specific slopes are two open pit of iron ore. One field mapping campaign was carried out collecting geomechanical aspects of the rock mass, intact rock and discontinuities identified. Along with that, a structural oriented mapping was performed, resulting in a lithostructural and lithogeomechanical maps for the interest regions.

To carry out the diagnosis of the stability conditions of the slopes of the two pits, the treatment of geomechanical data was previously made, with geological-geotechnical structural mapping. The potential types of failure at bench level are defined, with prior information that made this work possible: geomechanical geological mapping; drill holes and geotechnical-structural zoning of pits considering direction and dip of structures.

These data made it possible to interpret kinematic analysis considering geometric conditions; definition of potential types of failures mechanisms and limit equilibrium stability analysis for every mechanism with probability of failure over 10%. for the different types of failures identified, allowing the definition of potential types of failure mechanisms with indication of corrective measures and recommendations. The development of the indicated procedures resulted in a diagnosis of the stability conditions in the context for two open pits for rock masses.

1.1 Site description

The two analyzed open pit are in the Quadrilátero Ferrífero mineral province (Dorr, 1969), in the Serra do Curral region, in the State of Minas Gerais, Brazil. Consists in a metassedimentary sequence of Minas Supergroup, in which the basal units are quartzites an phyllities, overlaid by itabirites, dolomites. The upper portion of the sequence has ferruginous quartzites, phyllities, schists and mevolcanoclastic units. The main unit is the itabirite in Itabira Group, which is the main iron ore. The current excavation intercepts the itabirites mostly.

The site is approximately 20 km from Belo Horizonte and can be accessed from BR-381, heading south, and then west.

2 METHODS

To define bench stability conditions for the slopes of the two open pits, it was necessary to define the analysis sectors for rupture conditioned by discontinuities (flexural toppling, wedge and planar). The existing lithotypes in the pit are: ISC (semi-compact itabirite); (Compact Itabirite), QTZ (Quartzite) and IF (Friable Itabirite), all considered with a friction angle of 30º.

For this work, five steps were necessary:

i) Select the regions that have only rock mass following the Bieniawski (1989) (rock mass classification I, II, III and IV), based on the geological-geomechanical mapping.

ii) Split the slopes in terms of direction, with angular variations close to 20º, based on the topography of the open pits.

iii) Define the sectors with the same direction in the open pit. With this methodology, 31 sectors were defined.

iv) Identify the main discontinuities families, based on the trace form lines and domains (Figure 1). Each domain has specific structures with the respective geological measurements (dip/dir and dip):

- Domain 1: Foliation (Sn) 169º/36º; Joint 2 (Fr2+) 310º/76º; Joint 3 (Fr3) 188º/73º and Fr4 169°/36º.
- Domain 2: Foliation (Sn) 159º/50º; Joint 1 (Fr1) 063º/64º; Joint 2 (Fr2) 130º/83º and Joint 3 (Fr3) 204º/73º.
- Domain 3: Foliation (Sn) 173º/29º; Joint 1 (Fr1) 082º/67º; Joint 2 (Fr2) 144º/82º and Joint 2+ (Fr2) 332º/79º.

Where Fr2 is a verticalized joint and it is variation is represented by Fr2+.

v) With the information from items i to iv, a kinematic evaluation was carried out in Dips 6.0, from RocScience. This analysis consists of verifying whether there is a geometric relationship between the discontinuity or a set of discontinuities that favors failure for a slope under analysis, considering the direction and dip angle of the assessed slopes; the direction and dip angle of the discontinuities and type of failure expected for the situation.

vi) The sectors with potential for planar failure, wedging and/or toppling identified in step v, that is, with more than 10% (Wesseloo and Read, 2009) followed for deterministic limit equilibrium analysis with the litotype-specific scenario.

Were used Rocscience company softwares: Swedge 7.0, Rocplane 4.0 ans RocTopple 2003, applied to wedge, planar and toppling failure analyses, respectively. The discontinuity strength criterion proposed by Barton-Bandis (1982) was used. The factor of Safety for the stability condition was above 1.3. The angle that causes rupture was also estimated for the condition assigned.

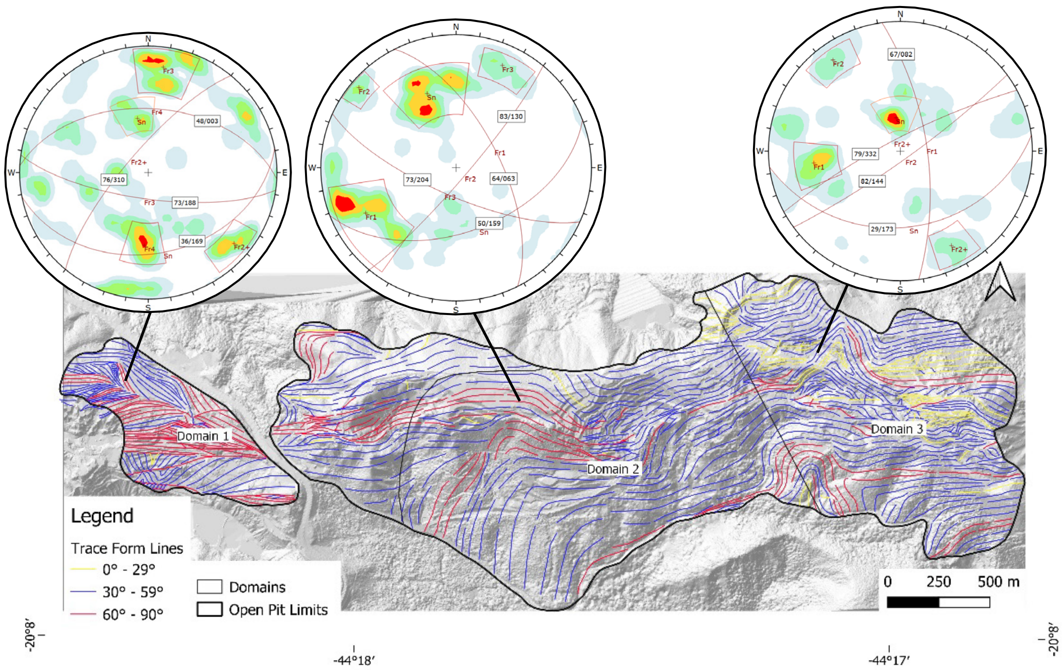

Figure 1. Trace form lines map, with three open pit structural domains. Domains 1, 2 and 3, represented by stereograms of equal area of the southern hemisphere.

3 RESULTS

Of the 31 sectors identified (sectors defined by the direction and composed of rock mass – classes I, II, III and IV), 21 presented a condition for some type of rupture by the kinematic analysis. Are They: 3, 5, 6, 7, 9, 10, 12, 13, 16, 17, 18, 19, 20, 21 ,22, 23, 24, 28, 29, 30 and 31. Considering the bench deterministic limit equilibrium analysis with the design parameters, only 4 sectors showed some condition for failure: 16, 29, 30 and 31.

As result of this approach, no sector presented conditions for wedge failure. For planar failure, the sector 16 shows rupture potentiality for Fr4 Joint. About Flexural Toppling, the sectors 29, 30 and 31 exhibited conditions for this failure for Fr1 Joint.

After kinematic and limit equilibrium analysis, the Table 1 presents the results with conditions for the occurrence of limit equilibrium rupture, only with the critical sectors, this is, with Factor of Safety below the norm (1.30).

The map with the open pit, analysis sectors and critical sectors is illustrated by the Figure 2.

Table 1. Limit Equilibrium results for sector with safety factor values below the norm.

Failures	Sector	Slope Angle (º)	Joints	Lithotype	FoS	Safe Angle to Slope (º)
Toppling	16	60	Fr3	SCI	-	43
Toppling	16	75	Fr3	SCI	-	43
Plane	16	75	Fr4	CI	1,03	48
Toppling	29	60	Fr1	CI	0,74	43
Toppling	29	65	Fr1	CI	0,68	43
Toppling	30	65	Fr1	CI	0,64	37
Toppling	30	60	Fr1	CI	0,67	37
Toppling	31	55	Fr1	CI	0,69	28
Toppling	31	65	Fr1	CI	0,62	28

FoS= Factor of Safety

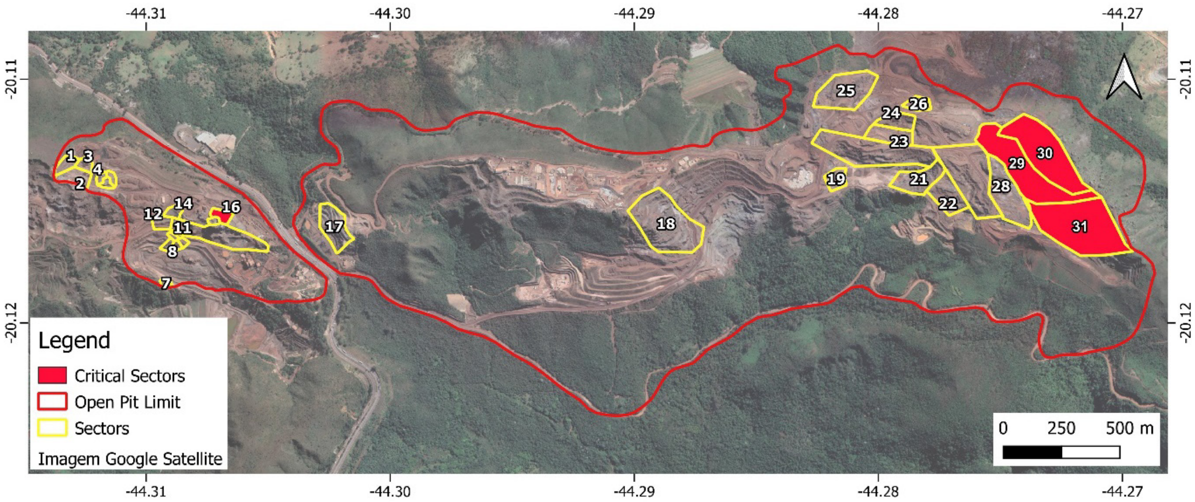

Figure 2. Sectors defined by direction of the slopes and with rock mass (I, II, III and IV).

4 CONCLUSIONS

The assessment of the operational slopes of two open pit mines shows valid analysis for the pit scenario at the time of analysis in November 2021. According to the development of the excavations, constraints not detected by this work may appear, requiring reassessment with the procedures presented.

It is important to respect the regions with rock (geomechanical class I to IV), since this method does not apply to unconsolidated materials (soils and decomposed rocks, without discontinuities).

No sector presented a wedge failure condition. Regarding flexural toppling, four sectors (16, 29, 30 e 31) presented unsafe conditions for the proposed pit scenario. Only one sector (16) presented a condition for planar failure, coincident with one of the sectors with a condition for wedge failure.

To ensure safety for the four critical sectors (16, 29, 30 and 31), the recommended angles are, respectively: 43º, 43º, 37º and 28º. Given the very conservative angles for the purpose of the ming pits, the recommendation is to change the direction of slopes located in critical sectors, eliminating even the kinematic condition of occurrence of ruptures.

ACKNOWLEDGEMENTS

The DF+ Engenharia team, for always focusing on technical quality and for the pleasant work environment.

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