Map of the potential geotechnical susceptibility for operational pit slopes

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Abstract

This article proposes a procedure to elaborate a map that presents the potential risk of failure occurrence in the operational slopes of open pit mines. First, it is necessary to collect the available geological-geotechnical data and perform a field mapping, in order to verify and validate the most representative parameters and to characterize the discontinuity families of the rock mass. Then, the mine should be sectorized, considering all the data collected, the geometry of the operational slopes and its development until the final pit. The next step will be to define and to evaluate which failure modes have greater or lesser potential to occur in the pit and to assign weights to them. In this study, the weathering, planar failure, and plane circular failure potentials were evaluated. As a result, it is possible to develop a map with the susceptibility level of the sectors. This map will help make technical and managerial decisions in order to reduce the risk level of the sectors and to promote an increase in the operational safety of the mine.

keywords: mining, room-and-pillar safety, numerical modeling, ore recovery.

1. Introduction

What is risk? Brown and Booth (2009) define risk as the chance of something happening and having an impact on the goals of the entrepreneur. Risk is inherent in various human activities and may be associated with a major accident or natural disaster. In any enterprise, failure in the process of controlling the associated risks can result in irreparable loss of life and property, besides influencing the ultimate objectives of the enterprise itself.

The Australian Standard AS/NZS 4360 (2004) establishes some procedures that guide the proper elaboration of the risk management process. In general, the standard recommends complying with the following steps: establish the context to be evaluated; identify all risks involved; analyze the risks related to the existence of controls; assess the level of criticality; and propose a prioritization of activities to address risk.

Risk management must be constant; that is, there is a need to revisit the entire evaluation and control the process periodically, as there may be new or unknown situations that influence in the context, control or in the addressing of risk, even after several analyses have already been carried out.

In case of risk materialization, if the controls are not efficient and fail, the impact can be considered as catastrophic, and seriously jeopardize the operational continuity of the enterprise. Figure 1 shows the image of a mine slope failure in Bingham Canyon, which occurred in April/2013 in the city of Utah, United States, according Caldwell (2013).

This failure was considered by the site http://www.magnusmundi.com (Cesar, 2016) as the largest non-volcanic landslide ever recorded in the history of North America. The mine was 107 years old, and slope monitoring relied on an interferometric radar system and a network of seismographs, operated by the Utah University of Seismic Stations. In the morning of the failure, the radar system detected an increase in the acceleration of the slope displacement and the mine was evacuated, so there were no fatalities, only material losses: 14 trucks and 3 operational machines. The mine operation was suspended for a period of 7 months. The data shows a great example of the control efficiency applied to follow the risk evolution and to reduce the impacts of the failure.

In an open pit mine, the geotechnical risk "slope instability" is one of the main concerns for the management of the mining activity in a pit, due to the uncertainties and variability of the data and parameters usually used, as pointed out by Brown and Booth (2009).

With the purpose of assisting in the risk management steps of the mining activity process "Identifying and analyzing all the risks involved", this article suggests the elaboration of a map denominated as: Map of the Geotechnical Risk Potential.

In this map, the visual consolidation of the results obtained from the analysis of failure modes is presented, demonstrating where there is a possibility of occurring a potential risk that would affect the slope stability. It is hoped that with this, tool there will be support to direct resources in order to manage and control the risk of slope failure.

The development of this study is based on the publication of Read and Stacey (2009), which is a guide for the elaboration of projects for pits, since it consolidates the best mining practices.

The initial stage is the survey phase of the geological-geotechnical data of the rock mass. Read and Stacey (2009), cite that the geological and geotechnical investigation must meet the necessary criteria of the geological-geotechnical elaboration and structural model consistently, in order to characterize the rock mass with the maximum of fidelity.

Figure 1
Slope failure.
Bingham Canyon Mine. Utah / USA
(Source: http://www.mining.com)

During the operational phase, the detailed field mapping provides a more reliable geological-geotechnical description of the rock mass due to its greater exposure and improves the data accuracy.

This is an expensive activity and the developer must decide the cost-benefit of the investment to be allocated in the research and data collection for characterization of the rock mass. Also, there must be considered the complexity involved in the analysis to be developed with the expected level of reliability for the development of the mine process.

Another important point in the moment of data collection is the elaboration of the hydrogeological model, since this information is fundamental to evaluate the groundwater behavior and its influence on slope stability during the development of the mine in its various operational phases.

Sequentially, the determination of the rock mass resistance parameters is given after the compilation of all available data and updated field mapping. Along with the results of the rock laboratory tests, the geotechnical parameters of the lithologies identified in the mine must be defined. These data are the key to the rock mass geological modeling and to the preparation of the sections to be used in the stability study of the rock mass.

It is prudent to carry out the sectorization of the projected pit or operational phase pit, since the slope excavation direction significantly influences the potential for failure, whereas the discontinuity families and rock strength can be different in each region of advance of the mining. There must be evaluated the geometric bench parameters (bench height, face angle and berm width) for each sector of the pit, according with the strength parameters, geological structures (direction, dip, etc.) of rock mass and the potential failure mode.

Besides the stability of the slopes, the definition of the geometric parameters influences the choice of the mining methodology and the equipment for the mining operation. Therefore, these issues should be very well analyzed and defined in the design phase. However, if the slope stability assessments, in the operational phase, point to any instability indicator, the geometric parameters, designed and /or executed, should be evaluated and, if necessary, redefined.

The failure modes may vary by sector and depend on the type of rock that constitutes the rock mass. Hoek (2000) makes a proposition of the most likely failure modes to occur on slopes, whether excavated on heavily weathered rocks or on hard rocks.

The purpose of this study was to establish a risk level indicator composed by the combination of potential failure modes, and to represent the failure susceptibility of a slope in an operational pit, by presenting the result of these analyzes through a map that can help in the advancements in mining and development of the pit.

The frequency of this map updating must be predefined, requires that the slope parameters analyzed in a first assessment be periodically reviewed so that risk management is dynamic and accompanies the progress of slope excavation and the mining development.

2. Material and methods

Assuming that the geological-geotechnical modeling is completed, then it is necessary to perform a validation and update of the available data to elaborate the Risk Potential Map for operational slopes. Hence, the methodology proposed for the development of this study consists of three stages:

Step 1 - Data collection

The field mapping has the function of evaluating and recording the existing geological-geotechnical characteristics to update the geological-geotechnical model of the pit. The methodology of Bieniawski (1989) is proposed for the field mapping. In the interest of registering the measurements of geological structures and evaluating the physical characteristics of the rock mass, the geomechanical mapping must rely on the use of the following tools:

• 50m measuring tape- used to mark the observed points. For the accomplishment of the work in scale 1: 2000, the points must be marked every 20m of distance;

• Penknife and geologist hammer - used to assess rock strength;

• Clar Compass - used to obtain the measurements of the linear and planar structures identified at each point.

Due to the geological-geotechnical characteristics of the rock mass in each pit, the criteria and parameters, proposed by ISRM (2007), can be adjusted and complemented, to better characterize and represent the rock mass.

For evaluation of the degree of weathering in the rock mass, a criterion based on the mineralogical alteration of the matrix rock and the discontinuities must be set, considering the percentage of the rock mass altered in each point. The degree of consistency is related to the uniaxial compressive strength. In this way, the rock strength in the field must be estimated with the geologist hammer pick or with the use of a pocketknife directly in the rock mass. The degree of fracturing is estimated by the evaluation of the spacing between the discontinuities and the persistence of these discontinuities.

The mapping of geological structures aims to verify their spatial distribution and the influence they exert on slope stability. The discontinuities identified in the mapping should be recorded and measured:

• Alteration of the walls of the discontinuities is defined based on the mineralogical alteration evaluation of the filling material and its cohesion.

• Regarding the opening of discontinuities, the thickness between the walls of the discontinuities is evaluated.

• Roughness is defined from the appearance evaluation of the contact wall of the discontinuities, varying from flat to irregular.

• The RQD "***Rock Quality Designation***" can be estimated by the number of joints with spacing greater than 10cm and with the bench height persistence of extension for every two meters.

For the storage, treatment and spatial analysis of the data obtained in the field (geology and system of existing fractures, as well as the physical characteristics of the rock mass), the geographic information system ArcGIS® 10 was used.

During the field mapping, whenever an underground flow is identified in the slope, the groundwater conditions must be registered and incorporated in the analyses to define the rock mass class.

The class of the rock mass is obtained by consolidating the parameters evaluated in the field, reaching the value of the rock mass RMR index, according to the criteria suggested by the methodology of RMR Geomechanical Classification, proposed by Bieniawski (1989).

Step 2 - Analysis of failure modes

The failure mode of one slope is directly dependent on the geological and structural characteristics of the rock mass. The next topic, will present the location of the study area, with a brief description and characterization of its geological context, where the proposed methodology was implemented.

• Geological and structural characteristics of the study area

This case study was developed in the pit located in eastern portion of the geologic region denominated Quadrilátero Ferrífero (Dorr, 1969).

The climate at the study area site is high-altitude tropical, with dry winters and rainy summers. The average annual temperature is 19ºC. The average annual precipitation between 1976 and 2012 was approximately 1,860 mm, with 85 % of the annual precipitation occurring between October and March.

The deposits of the area are located in the Alegria syncline in a highly deformed zone on the eastern edge of the Quadrilátero Ferrífero (the Iron Quadrangle). The iron ore found in the area (itabirite) of interest is characterized by the presence of ore bodies strongly aligned with the orientation of the fold axes (Rosière and Chemale Jr, 1991).

This itabirite rock mass belongs to the Cauê Formation, an intermediate portion of the Itabira Group (Minas Supergroup), dated between 2.42 and 2.52 Ga (Babinski *et al.* 1993, 1995).

Problems related to water tend to be site-specific, especially in weak rock deposits where the hydrology and geology are often complex. It was therefore extremely important to have a comprehensive understanding of the area with regard to its geomechanical conditions before the design phase to characterize the properties of the rock mass in the area and facilitate pit designs appropriate to the site-specific conditions.

A limiting factor in the proposed open mine pits is the increased geological/geotechnical risks associated with higher water pressures and their effect on slope stability. These risks are the result of interactions between the site's geological, hydrogeological, geotechnical factors, and operational constraints (Sjöberg, 1996).

Geological-geomechanical superficial mapping and borehole geotechnical description of hundreds of samples has provided very good knowledge of the rock masses, and borehole logging has allowed identification of fracture sets as well as the recognition that these structures control groundwater flow in the area.

• Survey of failure modes

The pit should be divided into sectors, defined by lithology, geomechanical class, structural domains and the geometric characteristics of the slopes: height, angle and direction. These sectors are temporary and dynamic, since the development of the mining is constant until reaching the final pit geometry, so they should be periodically checked. For the pit, reference of this study, the possible failure modes identified were defined according to the characteristics of the rock mass:

• Failure Potential by erodibility;

• Planar failure potential by kinematics;

• Plane circular failure potential.

• Evaluation of the potential for failure by erodibility

In order to obtain the erodibility failure potential, erosion processes in the mine are recorded during the field mapping. The number of records of erosive processes and their condition, multiplied by the numerical factor corresponding to the predominant degree of weathering, results in the sector's erodibility class, varying from Low to Very High, according to the score.

The numerical factor mentioned has the function of considering the level of mass weathering in the analysis. The higher the degree of change, the greater the potential for erodibility. A less weathered mass means a rock that is unweathered, harder and has less potential for erodibility.

Table 1 presents the proposed criteria to evaluate the degree of weathering of rock mass and the condition of erosion processes installed on the slope to obtain the failure potential by erodibility.

Registered Erosion Score		Degree of weathering Score		Erodibility Potential (A) x (n of erosions) x (B)	
Erosive processes recorded	Score (A)	Degree of weathering	Multiplier Factor (B)	Erodibility potential class	Interval
There is no record of erosive processes	0	W1	1	Low	<30
Record of small erosions (affecting drainage devices or 1 bench)	3	W2	1	Medium	30 <50
		W3	1	High	50 <70
Record of medium erosions (affecting up to 2 benches)	7	W4	1	Very high	>70
		W5	1.5		
Record large erosion (affecting more than 2 b benches)	10	W6	2		

Table 1
Criteria to obtain the classification of the failure potential by Erodibility.

• Evaluation of the planar failure potential by kinematics

The probabilistic kinematic analysis of failure is very representative in rock masses with the compositional bandaging being the main structure and conditioner for the slope stability. It takes into consideration the anisotropy of the material, the discontinuity families and the degree of alteration identified in the field mapping. These parameters are essential to evaluate the failure probabilistic of one slope.

In the mine where this study was carried out, the characteristic of the rock is very similar to soil, but the compositional bedding is possible to observe and to evaluate the probability of failure induced or conditioned by the existing discontinuities.

In very weathered rock mass, it is possible to say that the failure mode most likely to occur is plane-circular; that is, by the compositional bedding and other discontinuity families.

The probability in the slopes is indicated by the percentage of critical intersections of the planes: discontinuities mapped (dip direction/dip), and inclination and direction of slope excavation.

The kinematic analyses were performed using the software Dips v7.0, developed by the company Rocscience.

The percentage of critical intersections obtained in the kinematic analysis, multiplied by a numerical factor, presented in Table 2, has the function of inserting the potential in-depth extent of failure damage in the analysis performed. The product of this operation is denominated as the classification of the potential of the sector, varying from Low to Very High, as related in Table 3.

Probability		Planar failure Potential class
	< 30%	Low
> 30%	< 50%	Medium
> 50%	< 70%	High
> 70%		Very High

Table 2
Multiplier factor as a function of damage potential.

Numerical Factor	Damage Potential
1	Insignificant
1.3	< bench (24m)
1.4	One bench (24m)
1.5	> 2 benches < 4 benches (24m)
2	In-depth Extent

Table 3
Classification of the planar failure potential.

• Evaluation of plane circular failure potential

The evaluation of the potential circular failure of a slope is obtained through the analysis of stability of the critical section for each sector, using the strength parameters obtained in the laboratory test and rock mass class as reference. The lithology border condition was defined by the geological model data.

The criterion for defining the plane-circular failure potential is the critical analysis of the potential failure curves and their respective safety factor (SF). The plane-circular stability analyses were performed using the Slide v6.0 software developed by Rocscience.

The failure damage potential should also be considered: that is, if failure affects a bench, more than one bench, or if it affects the overall stability of the slope, according to the score for each condition presented in Table 4.

The classification of the sector related to the potential of the plane-circular failure is given by the sum of the scores in Table 4. The score obtained for a section gives the slope classification, and it varies from Low to Very high according to the class range presented in Table 5.

Table 4
Table of scores for the evaluation of plane circular failure potential.

Safety Factor (SF)	Range of the potential failure			
	Bench	Up to 3 Benchs	More than 3 Benchs	Global
NA	0	0	0	0
FS>1.5	0	0	0	0
1.3>FS<1.5	0	0	2	4
1.1>FS<1.3	2	4	8	10
FS<1.1	3	8	10	10

Table 5
Classification table of plane-circular Failure Potential.

Score	Potential class of circular plane failure
0 - 6	Low
7 - 15	Medium
16 - 28	High
29 - 40	Very High

Step 3 - Elaboration of the geotechnical risk potential map

The map of the geotechnical risk potential of the sectors is elaborated from the analyses in order to verify the stability and integrity of the operational slopes involved. From the results of these analyses, it is possible to classify the failure potential by failure mode, and according to the class, a score is assigned, as presented in Table 6 and in this table, a weight is proposed for the failure modes analyzed.

Table 6
Failure mode weight table and scores by risk class.

Failure mode	Weight	Class of failure potential	Classification by class
Failure potential by erodibility	10	Low	2
		Medium	4
		High	6
		Very high	10
Planar failure potential, by kinematics.	8	Low	2
		Medium	4
		High	8
		Very high	10
Potential for plane-circular failure	7	Low	2
		Medium	4
		High	6
		Very high	10

The score obtained by class of the failure potential, multiplied by the weight assigned to the failure modes, gives the indicator of the failure Risk Level for each slope of the pit, thus classifying the slope as to its Potential Risk, as it is presented in Table 7.

Table 7
Geotechnical risk level table.

Risk Level		Potential Risk Classification
0	165	Low
166	330	Moderate
331	495	High
496	660	Elevated

3. Results

The result of this process is a tool that consolidates several slope stability analyses, considering the influence of each possible failure mode and promoting slope failure. This proposal materializes a risk level indicator for each slope sector and composes a map, denominated as the Geotechnical Risk Potential Map.

In Figure 2, a proposed map model is presented. It should be emphasized that the data used are hypothetical, just to show the methodology applied and the map is an example of consolidated result, which demonstrates the geotechnical level risk indicator in each area of the mine.

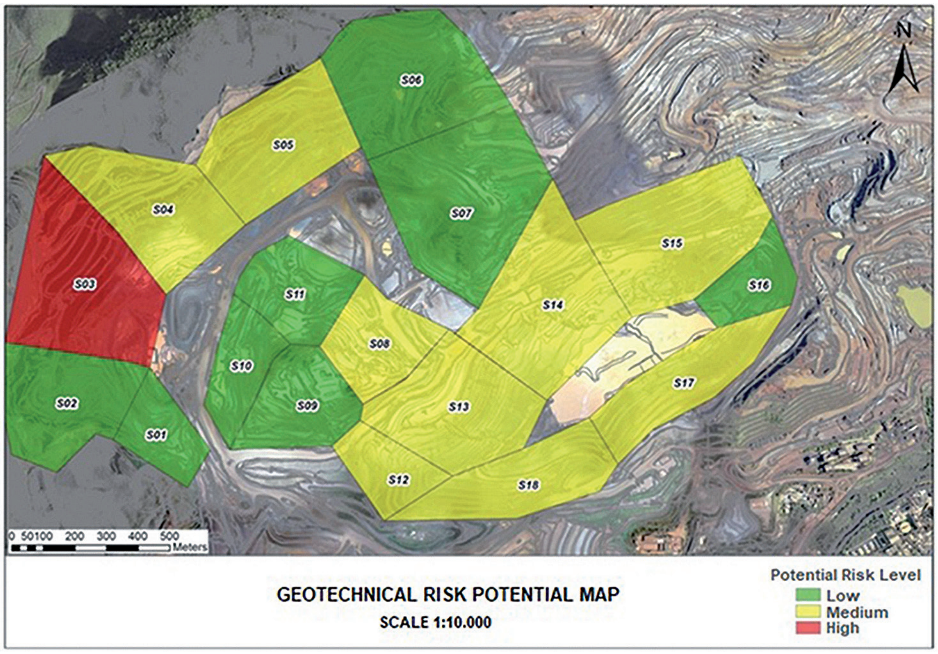

Figure 2
Example of the geotechnical
Risk potential map of a studied pit.

4. Discussion

The elaboration of a map that presents the potential of geotechnical risk of the pit, addressing all the failure modes with potential for failure, can make a great difference in the identification, analysis and evaluation of the risk, which can significantly contribute in the management of occurrences in an event compromising the rock mass stability.

The map can be a major reference in the definition of the slope monitoring plan, where slopes with a higher risk level should be given more cautious attention, thus meaning a greater frequency of geotechnical inspections, as well as a monitoring plan and greater control of the analyzed failure.

This tool can help guide the analysis frequency of the geotechnical parameters used in the risk assessment, define criteria to be taken and indicate the prioritization of mitigating actions and risk control.

During the risk analysis process, it is prudent to carry out a sensitivity and trustworthiness check of all the studies performed, mainly during the failure mode assessment step.

All the work developed must meet the existing technical standards and follow the "best practices" of geotechnical engineering. The reliability of the data processed must be guaranteed and met, due to the great number of uncertainties and the variability of the geological and geotechnical parameters dispersed in the same area.

The consequences of a slope failure should be assessed, considering personal injury or fatalities, damage to assets and the environment, loss of production, loss of licenses and the negative impact on the company image.

5. Conclusion

This tool proposes a systematic evaluation of the operational safety of the mining process, based on the analysis of failure modes, which influence slope stability, assigning concepts of risk management (probability X consequence) to classify the sectors of the pit by its indicator of the Risk Level.

It can be concluded that the proposal contributes to the fact that the Risk Assessment of slope failure is clearer and more focused, reducing the subjectivity of the analysis, besides systematizing and parameterizing the data of the rock mass and the analyzes of potential failure of the slopes sectorized from the pit.

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