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The FMEA Methodology Applied In The Risk Map For An Open Pit Mine

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ABSTRACT
Mine accidents can be prevented if risks are identified and mitigated by creating barriers through risk management to reduce the likelihood of Material Undesired Events (MUEs). The FMEA methodology – Failure Modes and Effects Analysis is cited in international risk management standards and is already used in mining and traffic to identify and propose preventive and mitigating controls associated with the risk scenario for the geotechnical structure. In this study, an FMEA was analyzed for an open pit mine in the Quadrilatero Ferrífero whose evaluation considered information regarding inspections and instrumentation, historical occurrences regarding geodynamic processes in addition to a lack of operational discipline. The scenario is identified and depending on its classification in terms of probability and severity will lead to critical action to reduce the risk. From the creation of the risk map, it is possible to represent, through graphic information, the risks identified in a geotechnical structure. The structure was sectorized by operational sectors and evaluated according to its reported nonconformities. In this context, the present study associated the risk map with the FMEA as the anomalies identified with the initial event and the failure modes with the undesired event according to the possibilities of occurrence.

KEYWORDS: MUEs, FMEA, risk management, mitigation control, risk map

1 INTRODUCTION

Hazard and risk analyze are essential for the Evolution of projects, resulting in safe deliveries and greatest reliability for customers. According to ISO 31000 (2018) risks can be defined by the effect of uncertainties on some objective. In the brazilian mining risk analyzes came into the agenda with greater force after the disasters involving dams.

Some documents such as GISTM (2020) indicate necessary improvements in the mining production process aimed at their sustainability, and among their primary factors is asset risk management and open communication with society. By this way risk assessments about dams have evolved significantly in recent years, but there is a need for developments in risk assessments involving other types of structures, such as open pits. “Risk analysis is the examination of how the different factors at play may interact, what scenarios may result from them and what losses they may cause. This process thus provides the possibility of identifying how uncertainties can combine and how this combination results in unfavourable scenarios.” (Maranha das Neves, 2002)

Large open pit projects are divided into regions, where the materials variation, types of contact, common anomalies, among other aspects that make a single and focused risk analysis difficult, as is carried out for dams and waste piles.

By observing these difficulties, this work proposed to carry out risk classification using the FMEA methodology of different regions of an open pit in the Quadrilatero Ferrifero considering each one its particularities and different failure modes, plotting the result in a risk map for users of the structure to view.
In a mine it's possible to finds different scenarios with certain severity levels, wich define a MUE. The failure modes in an open pit slope can be predicted during the design according to the geological and geomechanical characteristics of the massif. The economic exploitation and the necessity of geometry optimized could impact the structure stability. Another important point is throughout the development of the mine according to the execution of the excavation during a life of mine. The risks analyze in all stages of a mine could show the steps need to be considered to maintain the hazard control.
It is not enough to make the classification and management it is believed that the risk communication is essencial to keep the people involved aware of the risk they may be exposed to. Thus, based on the FMEA classification, a risk map of a mine in Quadrilatero Ferrífero was elaborated.

2 THE FMEA

The FMEA methodology was developed by NASA and the automotive industry and is responsible for identifying possible failure modes and their effects for a given product, asset or production system, Where through the eyes of evaluators it is possible to identify the probability of their occurrence as well as their severity. (GAYA; CHERRARED, 2023)

As demonstrated by Zhang, Zhang e Gong (2024), it is important that the analysis methodology is well defined if necessary with the use of more than one method so that the individualities of each of the evaluators do not interfere with the final results of the evaluation. It is suggested that theses assessments be carried out by multidisciplinary teams generating an in-depth view of the topic.

To determine clear and direct standards some guidelines were defined for the classification of severity and probability in the FMEA matrix of this work, according to Table 1 e Table 2. When assessing potential severity, people and the environment were assessed. In the probability classification, aspects related to the occurrence of events initiating the failure mode in the region safety factor and information uncertainty were defined.

Table 1. Severity Ruler

People	Environment	Severity
Multiple fatalities in wich the cause is related to operational processes	The affected environment restores its integrity in more than 10 years after the event	Very Critical
1 fatality in which the causes is related to operational processes. Event that results in the multiple fatalities	The affected environment restores its integrity within 5 to 10 years after the event	Crítical
Events resulting in life-changing injury/illness or 1 fatality	The affected environment restores its integrity within 1 week to 5 years after the event	Significant
Events that result in injury/illness with absence from work or with medical treatment or work restriction	The affected environment restores its integrity within 1 week after the event	Moderate
Event that result in first aid	The affected environment does not lose its integrity (composition, structure, and functions)	Low

Table 2. Probability Ruler

Qualitative Risk Analysis	Category
A serious fundamental deficiency or defect. Is known to exist. There is a history of significant initiating events occurring once or several times a year and direct evidence of failure mode progression There are no controls designed	Very likely
A significant physical disability or defect is known to exist. There is a history of significant initiating events occurring up to once a year and some indirect evidence of small failure mode progression There are limited engineering controls and system-based controls for a failure mode or there is a history of frequent failure of controls implemented at the facility for a failure mode.	Likely
It is known that there is a disability or physical defect, however the defect is not serious. There is no history of significant initiating events occurring for failure modes associated with the deficiency and no evidence of progression of failure modes. There is at least one preventive engineering control implemented for a failure mode or several system-based controls and no history or failure of these controls at the facility and occasionally occur in the industry.	Possible
There are no physical deficiencies and no history of occurence of initiating events for failure mode in the structure. There is at least one preventive engineering control and on system-based control implemented for the failure mode and no failure history of these controls at the structure or at any other site, however failures have occurred in the industry for failure modes and conditions similar.	Remote
There are no physical deficiencies and no history of occurrence of initiating events for all failure mode in this structure.	Very remote

During the preparation of this work a 5x5 matrix was considered to classify risks, where through the classification of probability of occurrence and indicated severity, it is possible to identify the risk classification varying between low (green), médium (yellow), high (Orange) and very heigh (red), as shown in figure 1.

The risks classification was considered inherent, residual, and projected scenarios. The importance of classification in these three aspects is given by verifying the effectiveness of existing controls in the processes and the need to implement better security barriers. Inherent risk represents natural risk, that is, the probability of a scenario materializing if the enterprise is not concerned with it. Residual risk deals with the scenario with the controls existing on the day of assessment. This classification is important for viewing and understanding the effectiveness of existing preventive barriers. If the residual risk is considered very high, which a good risk appetite does not allow, a projected risk analysis must be carried out considering the implementation of actions to reduce the level of this scenario.

The target of a FMEA matrix is to compile a list of credible failure modes for the geotechnical structure, that could cause a MUEs, considering the performance of the structure based on the activities and future operations at the site. The MUE is a combine of potential failure mode will define by a specific demand, root cause and initianting event. The analyses showed the effects of the materialization of this event.

In this work, the mine sectors were considered components of the system and each failure mode was classified according to the FMEA methodology. The risk assessment considers the probability ruler and severity ruler, where the combine of this classification gives a priority range from low to very high for each MUEs described considering industry experience with similar structure (Figure 1). The risks are classified by inherent if there is no control residual considering existing control and residual forecast after implementation of all critical controls managed so that full lifecycle of the Geotechnical Structure have the required reliability.

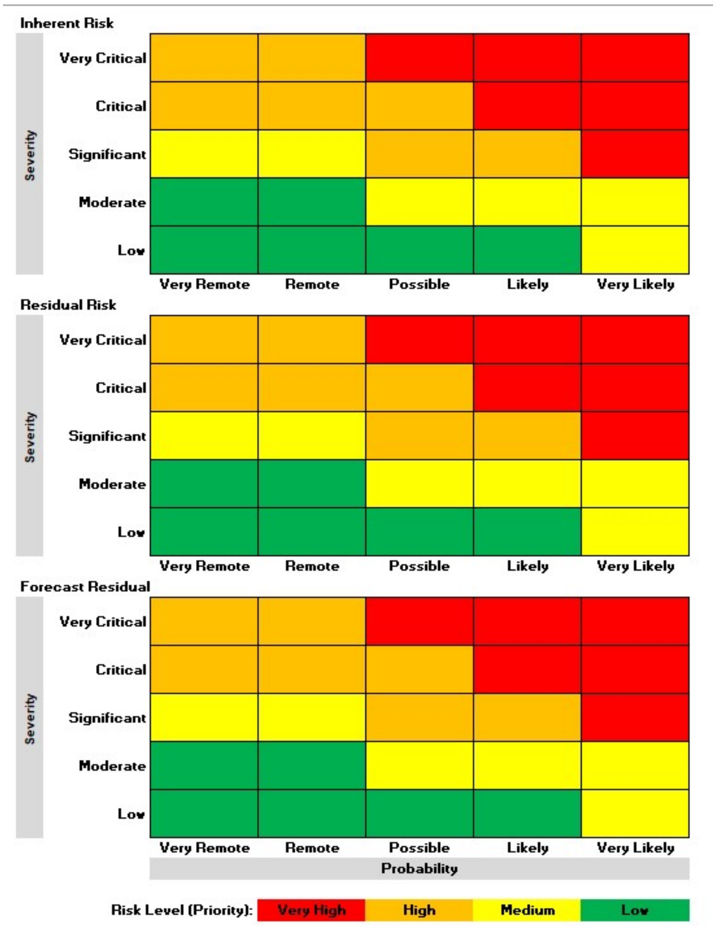

Figure 1 – FMEA RISK MATRIX

3 FAILURE MODE and ANOMALIES

A potential failure mode occurs whenever an imbalance takes place between shear strength and shear stress in the massive and. The triggering factors for slope failure could be linked to heavy precipitation, weathering conditions, seismic disturbances, and human activities. The failure slope known: plane failure, circular failure, wedge failure and toppling failure. The plane failure occurs when a structural discontinuity plane such as; bedding plane, fault plane or preferred orientations of a joint set dips or daylight towards the valley or excavation at an angle smaller than the slope angle and greater than the angle of friction of the discontinuity surface. (Raghuvanshi, 2019). “Although these are typical mechanisms of soil slopes, circular failure can also occur in rock masses, especially if it is made up of soft rocks, a material that has soil behavior due to its high degree of alteration and fracturing. Wedge failure develops from the existence of two or three discontinuities that intersect, forming an unstable block. The orientations of these elements are critical in the conditioning of wedge slippage, and for the rupture to occur, it is necessary that the inclination of the intersection line is less than the slope and that the friction angle along the planes of discontinuities is less than the inclination of the intersection. In addition, the sliding surfaces”. (Silva, 2010). Toppling failure are movements that involve the rotation of masses of soil or rock, relative to a point or axis located below the center of gravity of the displaced mass. In a fractured rock mass, the net force that determines the tipping is due to the weight of the blocks formed by the masses of soil or rock, the water pressure at the joints, and friction. (Azevedo e Marques, 2000). In the design phase the failure mode needs to be identified. The project of an open pit could be changed, or engineering controls implemented to solve the hazard identified.

The anomalies are events anomalous identified in geotechnicals inspections. This event could be caused by the materialization of a failure mode or could be operational deviation. The FMEA matrix evaluated, occurred plain failures, circular failures and other events arising of development of mine like inefficient drainage, overbreaks, pipping and block fall. This MUEs are evaluated and classified in each sector of the mine.

4 MATERIALS AND METHOD

The geomechanical classification and structural geology of the massif are the main sources of data on the possible failure modes to wich the slope is susceptible. This information will be the first look at creating controls that will minimize the occurrence of slope failures.After human intervention on the slope, geotechnical inspections will report the stability condition of the slope and will be a source of information for defininf the MUEs for preparing the FMEA matrix and risk classification.

The methodology consist of defining the operational sectors and evaluating the risk for each failure mode of concern to the sector. The map has a georeferenced image of the mine, the limits of the sectors and it will be hatched according to the highest risk defined in the FMEA matrix. The failure modes and anomalies represented by symbols in the place where they occur.

The map also presents the sectorization defined for radar monitoring that is an important information in the case of reaching a defined displacement level. As well as the control and mitigation actions proposed to reduce the risk. The matrix presented indicates the residual scenario found in the risk assessment that is, it considers the structure with the controls already implemented.

5 THE RISK MAP

The risk map (Figure 2) is an important tool to communicate the employes the risk that they are exposed in an open pit mine. The dynamic development of an open pit requires that it be update frequently. The update forecast of the FMEA matrix is 2 years but the scenarios of modes of failure and anomalies could be changed, and it could be modified on the map. As well as the mitigation actions could be implanted, and the risk classification could be changed for each sector.

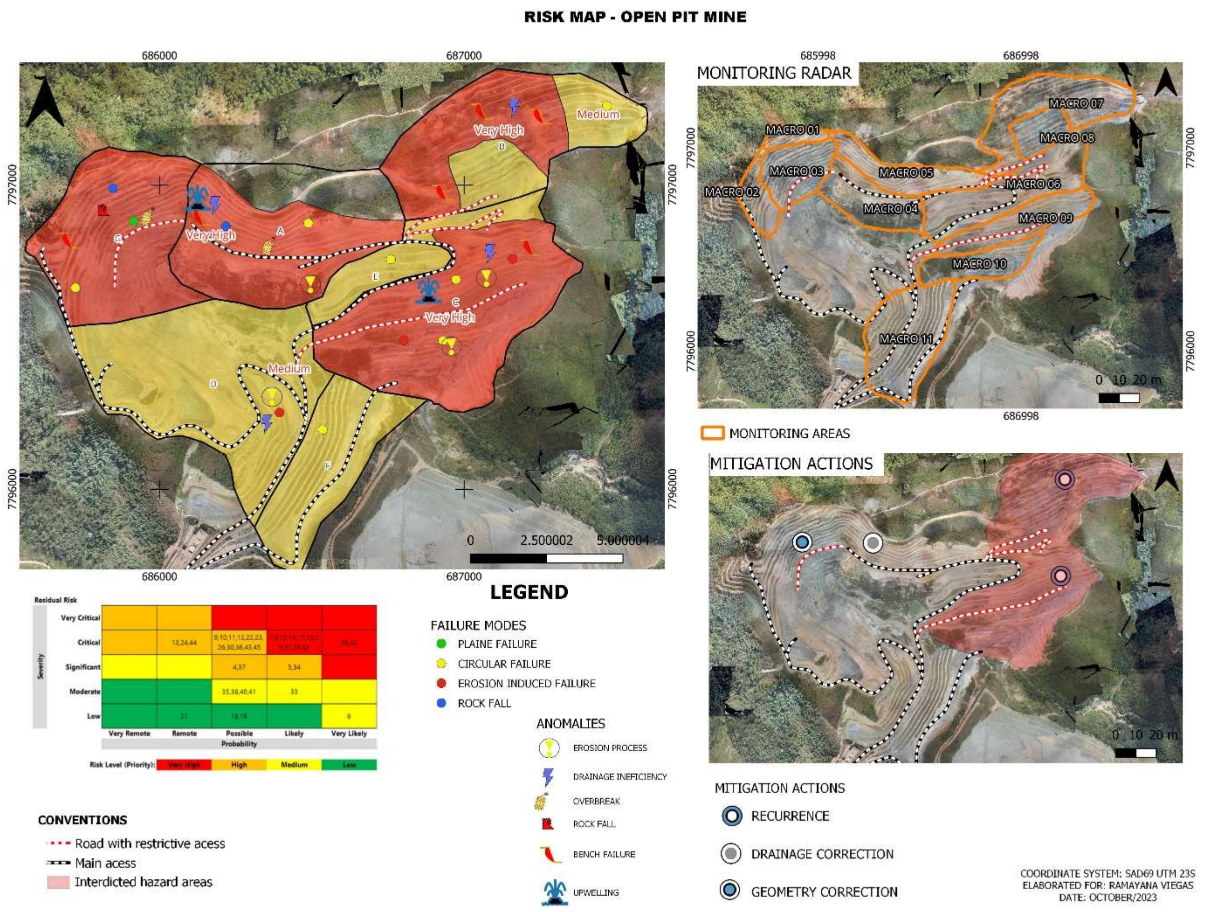

Figure 2 – RISK MAP

5.1 The Mitigating Actions

In the FMEA matrix, the critical controls that enable the reduction of the risk classification, in terms of the severity found, were described. The development of emergency plans, monitoring indicators for dealing with anomalies and preventive actions for the rainy season are examples of migration controls For each MUE described, actions were defined that, when implemented, also favor risk control, which are: preparation of the operation and maintenance manual, training for operators who perform activities in the pit, follow the adherence indicators, conclusion of drainage master plan, improvement of information about the massif, drillhole campaign, tests and hydrogeological model.

6 RESULTS AND DISCUSSION

The risk assessed and presented on the map will be the residual as it refers to current information about the mine, as it is today. According to the evaluation of the probability and severity matrix, 12 very high risk scenarios were found, 18 high risk MUEs, 6 medium risks. After implementing the proposed actions, we will no longer have high or very high risk scenarios, as can be seen in the forecast residual matrix (Figure 3).

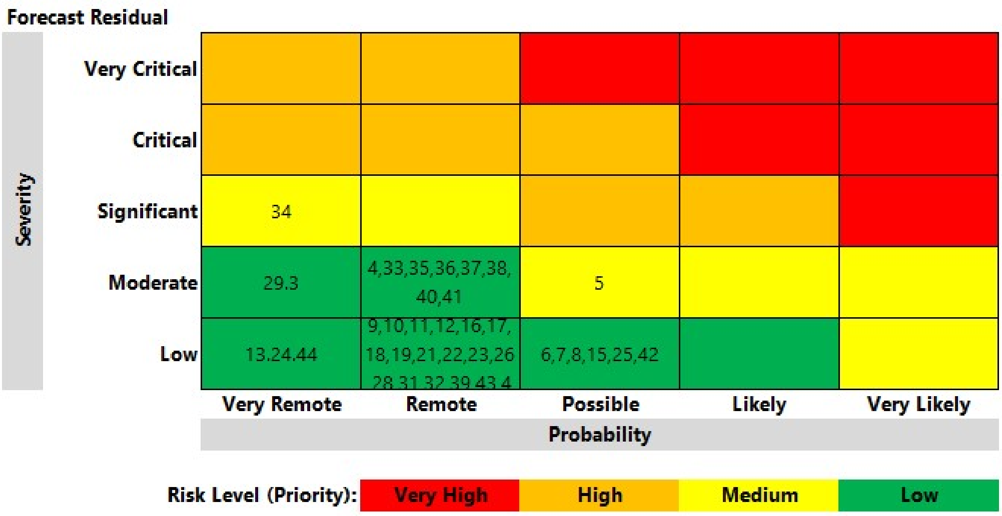

Figure 3 – FORECAST RESIDUAL MATRIX

The proposed controls are related to knowledge of the intrinsic characteristics of the structure, such as geology, geomechanical and hydrogeological behavior and the characteristics of the proposed project. As well as controls related to operational discipline and application of best mining practices such as the correct direction of drainage, verification of adherence of what was executed to what was planned, monitoring of preparedness indicators for the rainy season. Through these controls, it is expected to achieve the forecast residual risk and reduce operators' exposure to risk in the structure in question.

7 CONCLUSION

The risk map is an important tool for sharing the structure's risk information with employees. It does not reduce the risk, but it assertively reports the condition of the structure. The FMEA methodology proved to be assertive in identifying the MUEs that reduce the structure's safety condition. Through this identification, it was possible to define the appropriate controls to reduce the structure's risk.
Through the assessment, the average projected risk was arrived at for all sectors of the mine, which is expected for a place where people are working daily.

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