SSIM 2021 - PM Dight (ed.)
 ISBN 978-0-6450938-1-0
doi:10.36487/ACG_repo/2135_28

Improvement in operational continuity and risk management based on the integration of bench geotechnical condition and monitoring

M Vargas *TIMining, Chile*

J Bello *TIMining, Chile*

C Calderón *TIMining, Chile*

Abstract

Knowing the spatial distribution of the geotechnical face condition and the geometric reconciliation of the pit construction allows the operating geomechanical team to provide the location of sources of rocks that could fall, and the retention capacity that the berms available provide; this is relevant information for the management of risks that affect the continuity of the mining plan, compromising the economic value of the project (NPV).

Active areas warned by the geotechnical monitoring and potential instabilities identified near the operation also deliver records to support measures that improve the compliance of the mining plan.

A methodology which combines tools that automate the reconciliation of bench construction and the compliance analysis with the identification of possible instabilities helps to improve the compliance of the weekly short-term plan and sequencing. In this way, it is possible to duly warn the operation about the situations the drilling and loading teams will face daily.

This work proposes characterising the risk level of the daily units of the extraction plan according to the presence of active areas in the vertical line on the extraction polygon, geotechnical face condition, effective retention capacity of the berms located above the extraction polygon, and presence of containment elements, such as barriers and parapets.

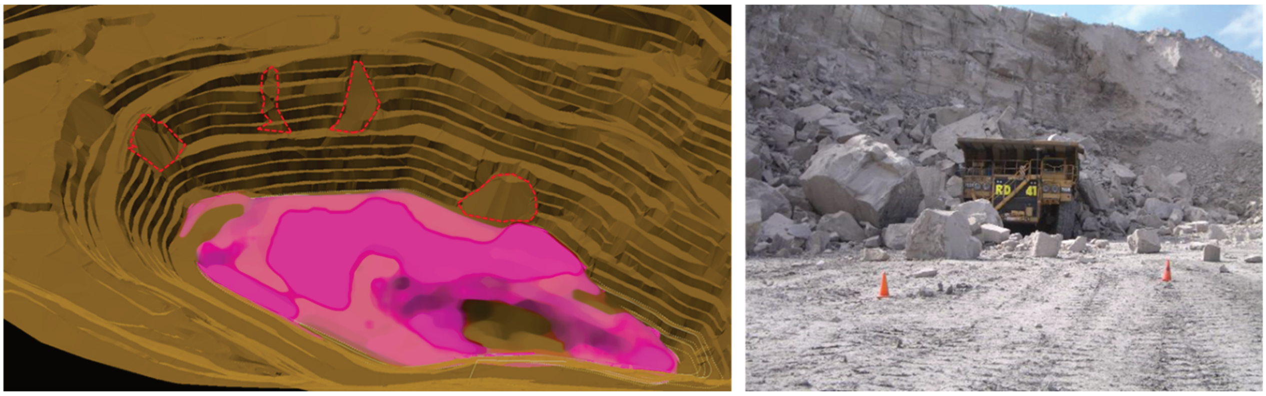
Finally, we propose a discussion about the reduction of uncertainty of the NPV or increase on it, which one can access based on:

1. *Objective records to study increase on angles and optimisations of the design.*
2. *Optimisation of the construction process.*
3. *Reduction of operational interruptions.*

Keywords: *risk, safety, operational continuity, geometrical reconciliation, geotechnical bench condition, monitoring*

1 Introduction

Improving compliance with the mining plan is becoming increasingly important, considering the constant changes in price cycles, and therefore the level of inventory required by mining companies, which makes the achievement of production goals more and more relevant. From this perspective, geotechnical discipline arises as a main element since it proposes design, analysis, follow-up, and control tools that provide relevant information for the coordination of the different teams in charge of the execution of the mining plan. Figure 1 shows how slope instabilities affect people and equipment in terms of operational interference and damage.



(a) (b)

Figure 1 (a) Inter-ramp scale instabilities potentially affecting future developments of the extraction plan; (b) Accident at the bench level affecting people and equipment

Given the scenario described above, it is essential to visualise the extraction process in a comprehensive manner and the way in which the parts that compose it are related, in order to meet the requirements of the construction of the pit. Another relevant issue is the technological capacity (computational and digital media) currently available, which allows adding digital elements to the process, enabling continuous feedback (Figure 2).

Figure 2 Simplified representation of the mining process of extraction of an orebody

From the integral perspective of the processes, there is a need to recognise the optimal slope design geometry, which seeks to respond to requirements related to the sustainability of the project, from the economic perspective, slope stability, and operational safety. Figure 3 shows a scheme with the key aspects considered in an optimal slope design, which was prepared using as a reference the explanations and schemes proposed in *Guidelines for Open Pit Slope Design* (Read & Stacey 2009).

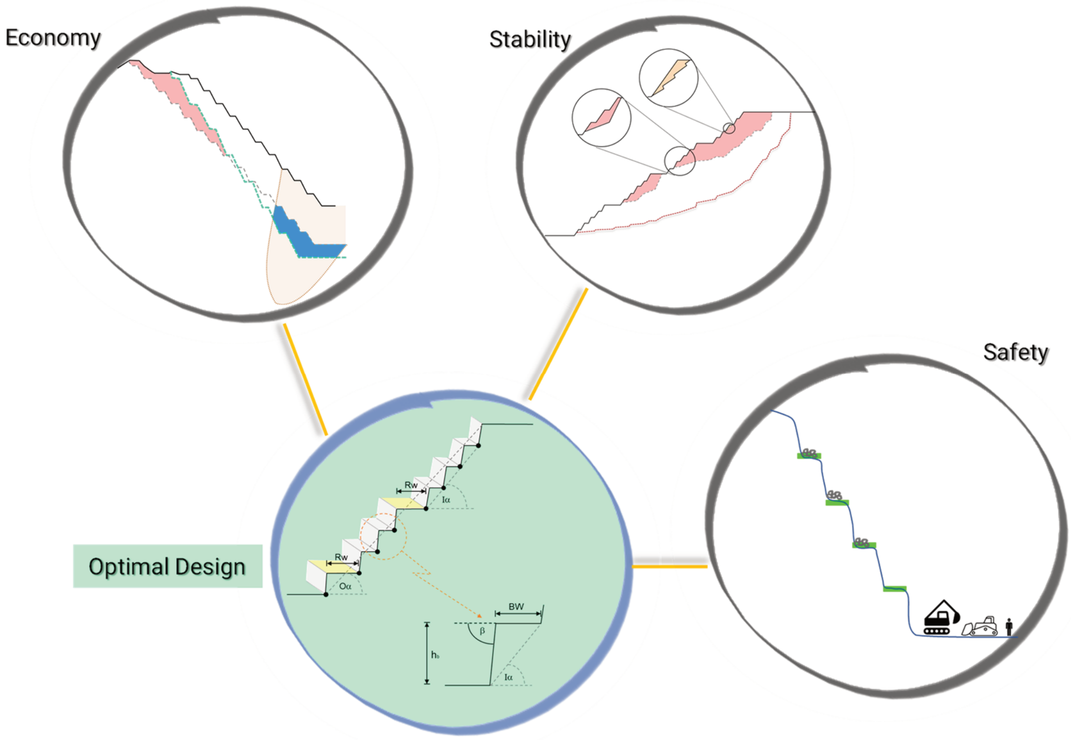
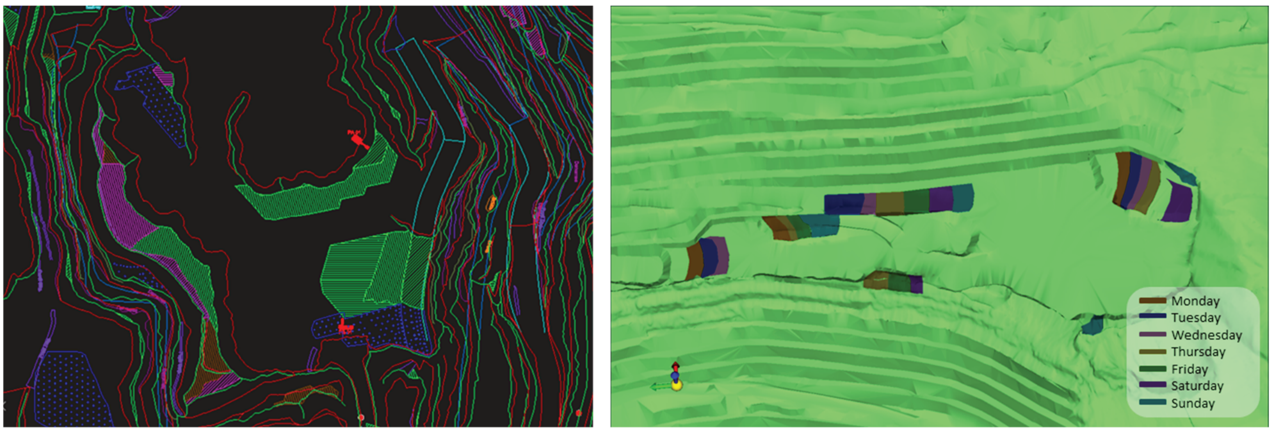


Figure 3 Diagram of the key aspects considered in optimal slope design

By integrating the optimal slope design requirements (bench–berm design parameters) to the extraction process, it is possible to have a global view that enables the identification of improvements in equipment sequencing and positioning planning, in order to ensure operational continuity and improve compliance with the mining plan, maintaining operational safety and sustainability of the project. Figure 4 shows two drawings that represent the spatial and temporal distribution (weekly) of the production equipment.



(a) (b)

Figure 4 (a) Representative plan of an extraction plan with the position of the equipment; (b) Three-dimensional view of the extraction plan for each day of the week

In this context of integration of the extraction process, in order to ensure and improve compliance with the mining plan, it is necessary to have evaluation methods and criteria to support risk management. Figures 5 and 6 show two methods for the evaluation of the constructed geometry and the face condition of the constructed slopes. These methods support management based on meeting targets set by the company for the quality of the pit slope construction.

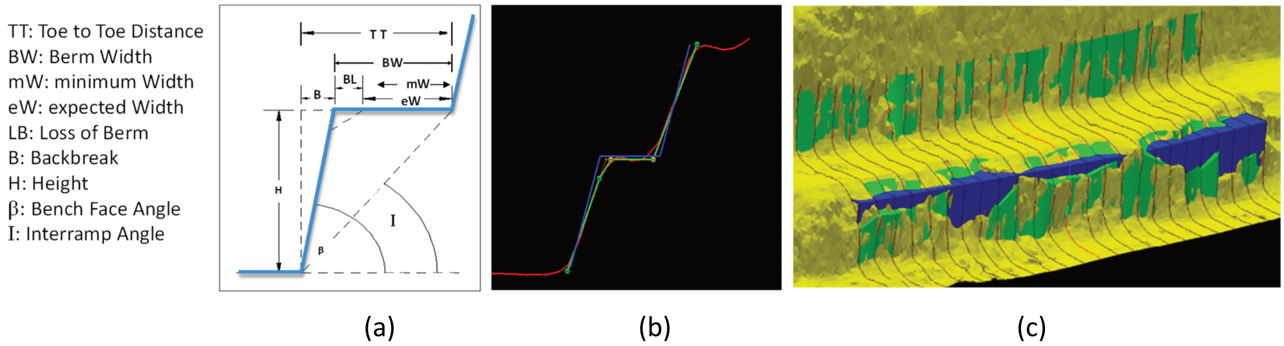


Figure 5 **(a) Sections with the optimal design parameters; (b) Reconciliation section between the design and the constructed slope; (c) Three-dimensional view of an evaluated slope. Images captured from TIMining-SICT software (TIMining 2021a)**

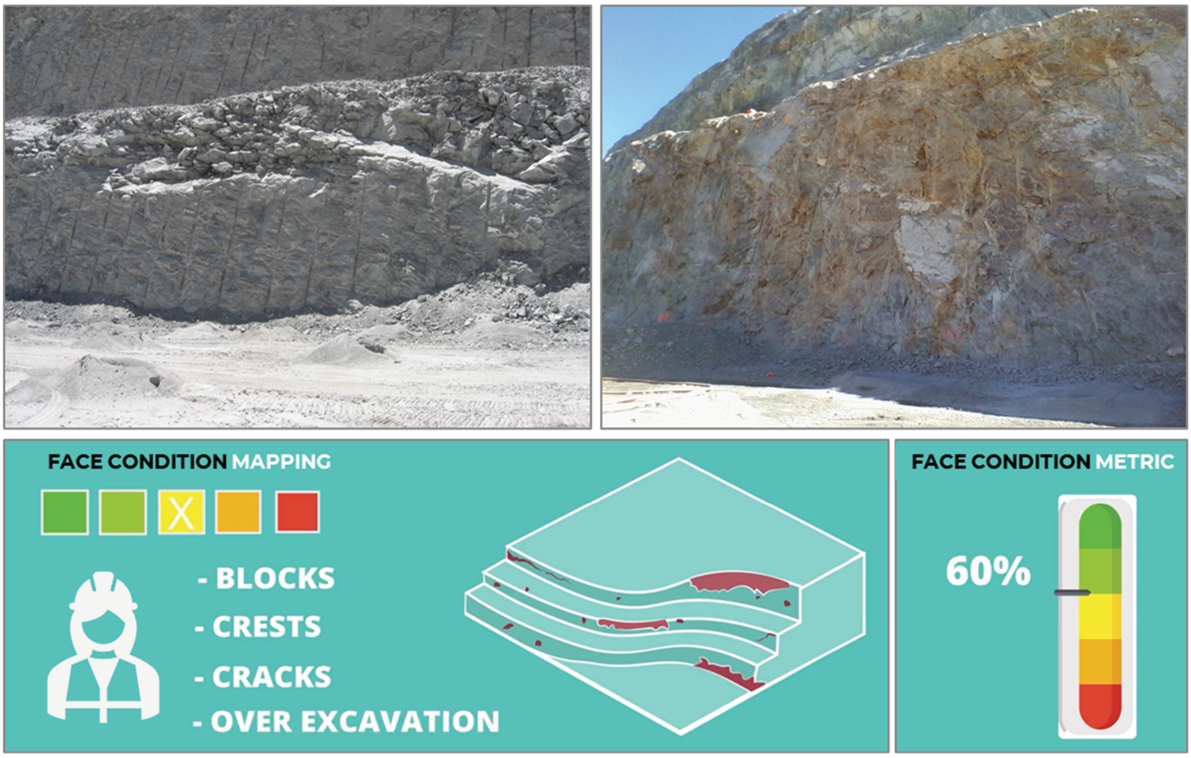


Figure 6 **Schematic diagram of damage and scaling assessment of constructed slopes**

The evaluation methods indicated above can be incorporated into the extraction process, enabling relevant information and control metrics called design factor and face condition (FC) (Read & Stacey 2009), which support the management of risks associated with compliance with the mining plan.

The elements described, integrated with the geotechnical monitoring of the slopes and the early detection of potential instabilities, allow the construction of a methodology for the characterisation of the existing danger in the different slopes of the pit, providing georeferenced geotechnical information, in order to warn in a timely manner about the dangers and risk levels that the progress of the extraction plan will face in the different time horizons.

The methodology proposed in this work is shared so that mining companies can support their risk management, favouring the operational continuity of the extraction process, and therefore the success of the mining plan.

2 Methodology: risk management and control actions

It is of high interest in the mining industry to have a methodology that supports the management of risks related to the compliance of the mining plan, which encourages continuous improvement of processes to increase productivity and profitability in a sustainable manner. In this context, the geotechnical discipline provides value in terms of information management, rock mass modelling, analysis and simulation of the different mechanisms that support the optimal design geometry. On the other hand, it proposes tools for follow-up, control, and feedback to the implementation of slope design.

With the intention of proposing a methodology based on historical expertise, we consider it appropriate to place ourselves in the concepts presented by the plan-do-study-act (PDSA) cycle of learning and improvement of products and processes (Deming 1993), which defines four perspectives for the management of processes, which are shown in Figure 7.

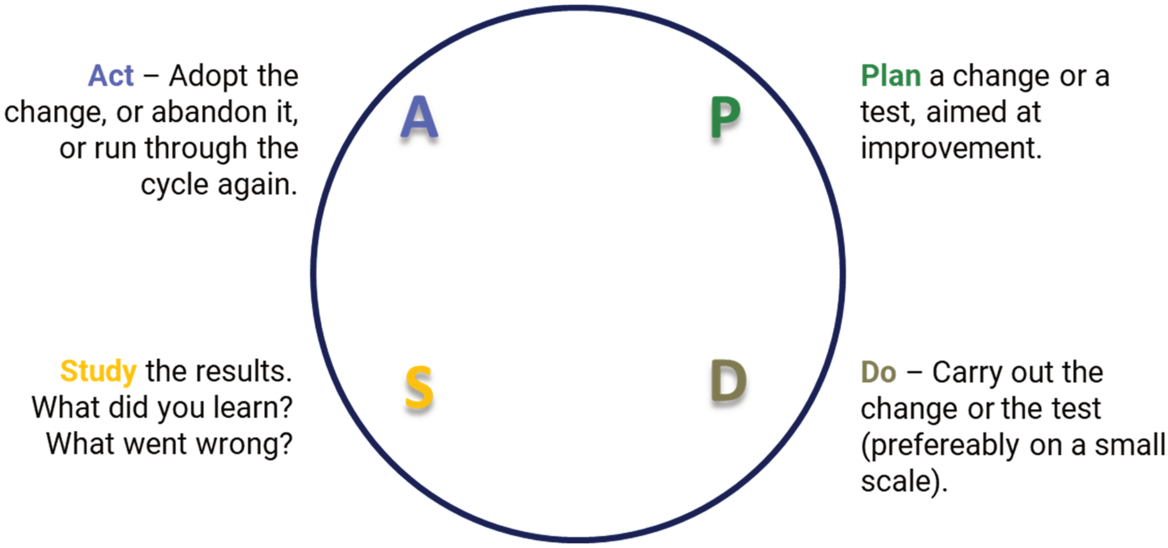


Figure 7 Plan-do-study-act cycle for process improvement

Using the process improvement cycle as a reference, we propose a methodology for managing the risks associated with compliance with the mining plan, which focuses on extending the domain of actions in the study area (study). The methodology considers four key tasks that consist of:

1. Visualise the geotechnical information of the mine in an integrated manner.
2. Characterise the patterns that emerge associated with the different conditions of the rock mass and operation of the mine.
3. Analyse, learn, and report the elements that put at risk the compliance of the mining plan.
4. Propose and implement improvements to mitigate hazards that could compromise compliance with the mining plan.

The points previously described can be organised in a circular fashion to generate a scheme as shown in Figure 8, which was built based on the visualisations obtained using the TIMining-SICT slope control software.

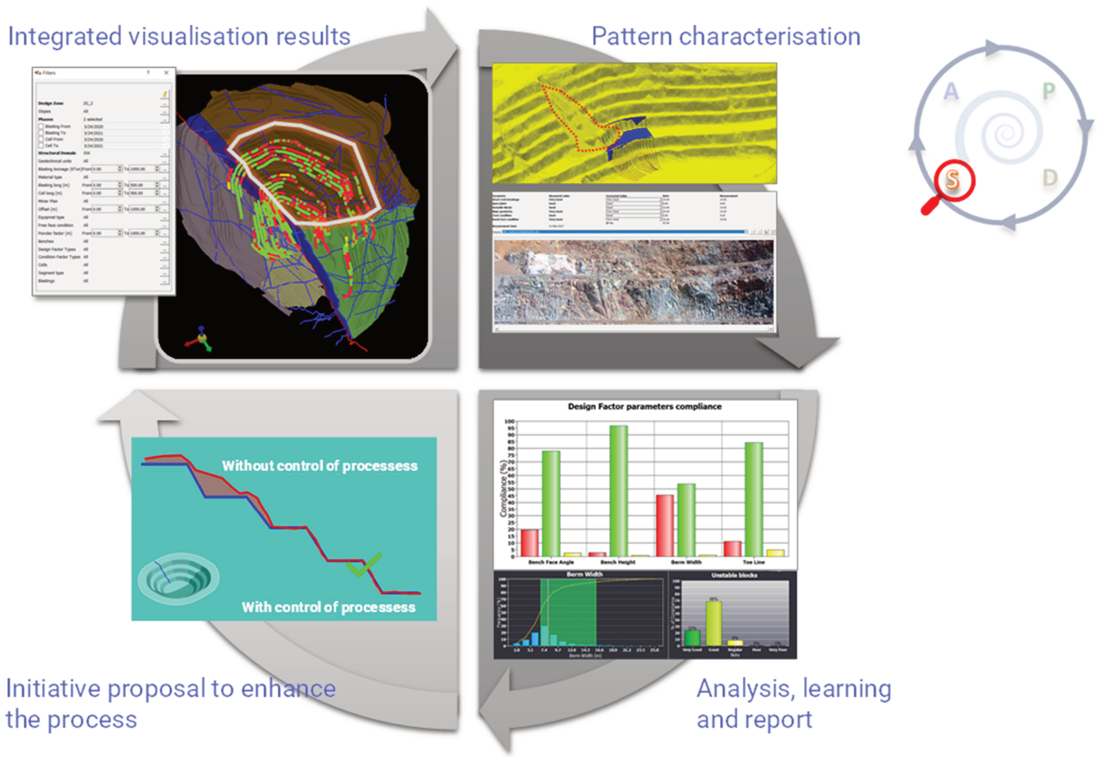


Figure 8 **Scheme for the extension of study tasks (S) during the extractive process. Images captured from TIMining-SICT software**

The scheme presented previously is oriented to provide situational awareness of the types of hazards present in the mine, their extent, and level of exposure. This is derived from the management of georeferenced information (three-dimensional) that allows one to visualise and alert in a timely manner to the people and equipment operating in the mine, improving the management and coordination between the different areas involved in the extraction process, favouring the result compliance with the mining plan.

3 Antecedents

The observation of a pit wall makes it possible to identify, visually or by technological means, elements that have an impact on the risk assessment of the operation and, consequently, on operational continuity. In this work we propose to work with the following elements:

1. Distance of the operation to the pit wall.
2. Containment by means of barriers or parapets, which protect the operation from rocks falling from the wall, as shown in Figure 9.
3. Berms for containment of rocks falling from upper banks.
4. Vertical interference of phases, especially in the inter-ramps immediately above or below.
5. Potential instabilities identified in the wall of the operating bench, as shown in Figure 10, which could fall at the time of removing the blasted material, with a high potential to affect loading and hauling equipment, in addition to delaying the normal rate of the operation.
6. Active sectors warned by geotechnical monitoring instrumentation (e.g. radar and total stations), as show in Figure 11, associated with potential instabilities at minor (bench), medium (inter-ramp), and major (more than one inter-ramp and global) scales.
7. Saturation of berms with rocks that are deposited throughout the life of the benches, reducing their retention capacity.

8. FC metric that accounts for the geotechnical condition of the benches. These are conditions that increase the potential for rockfall from benches, generally due to damage caused by uncontrolled blasting or inadequate loading practices (e.g. fracturing of the crest, over-excavation of the leg, and opening of cleats), as well as the presence of unstable blocks on the bench face due to lack of cleaning and scaling. Figure 12 shows field condition examples of crest fracturing and presence of unstable blocks.

Figure 9 Containment elements such as barriers and parapets

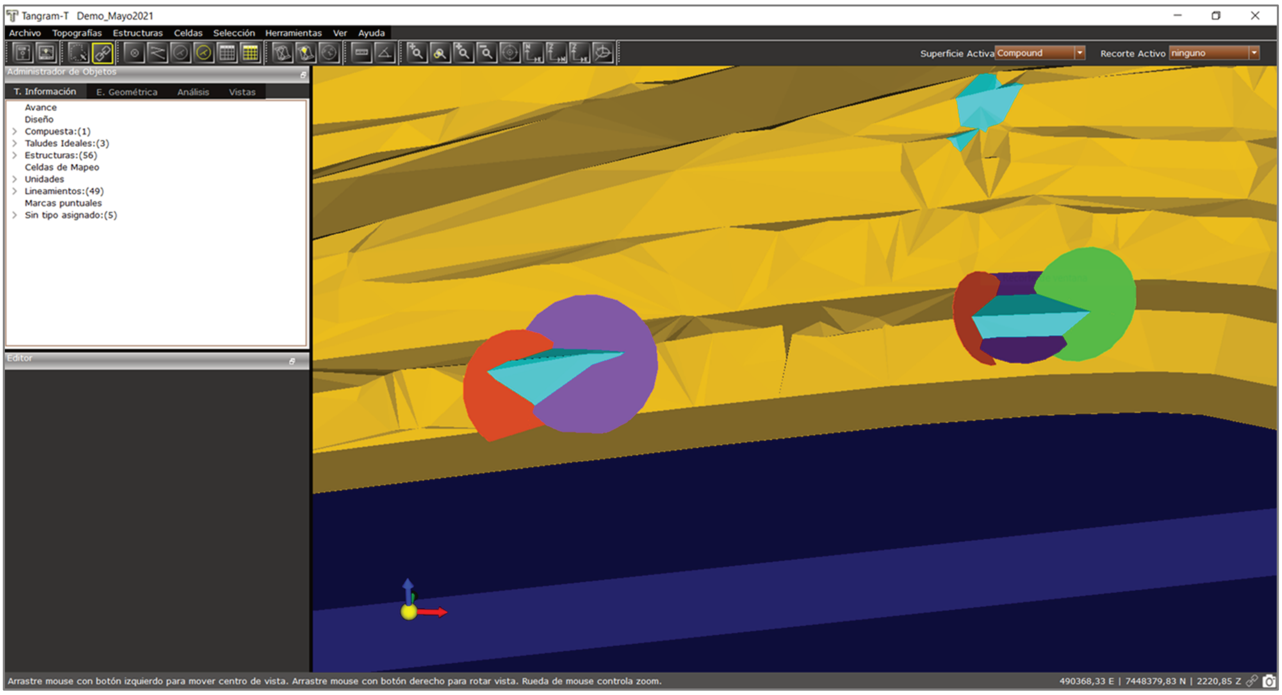


Figure 10 Projection and identification of potential instabilities in the operational area. Image captured from TIMining-Tangram software (TIMining 2021b)

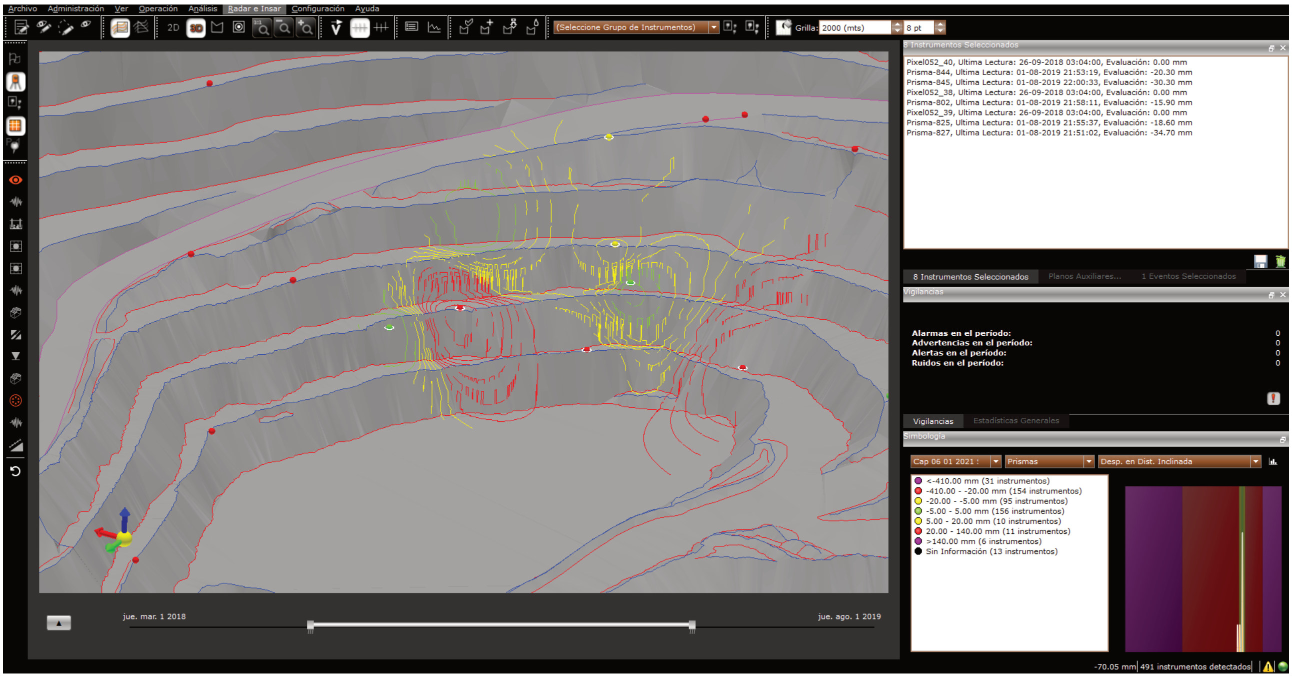


Figure 11 View of active sectors warned by geotechnical monitoring. Image captured from TIMining-Aris software (TIMining 2021c)

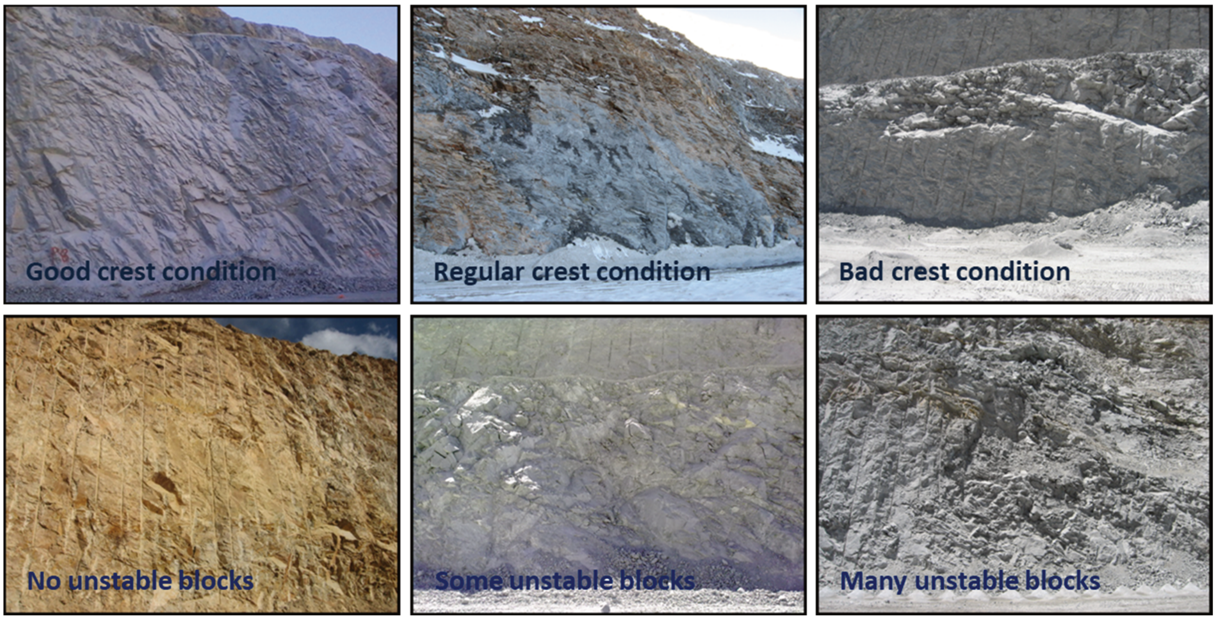


Figure 12 Evaluation examples of crest fracturing and presence of unstable blocks

An integrated spatial view, which relates the location and evaluation of the elements described with the areas where the drilling (blasthole drills) and loading equipment (shovels, wheel loaders and trucks) are working, will allow the operational geotechnical team to characterise the exposure of the weekly mining plan to the risks present in the wall. Figure 13 shows the results of the evaluations of different parameters that characterise the quality of the bench construction.

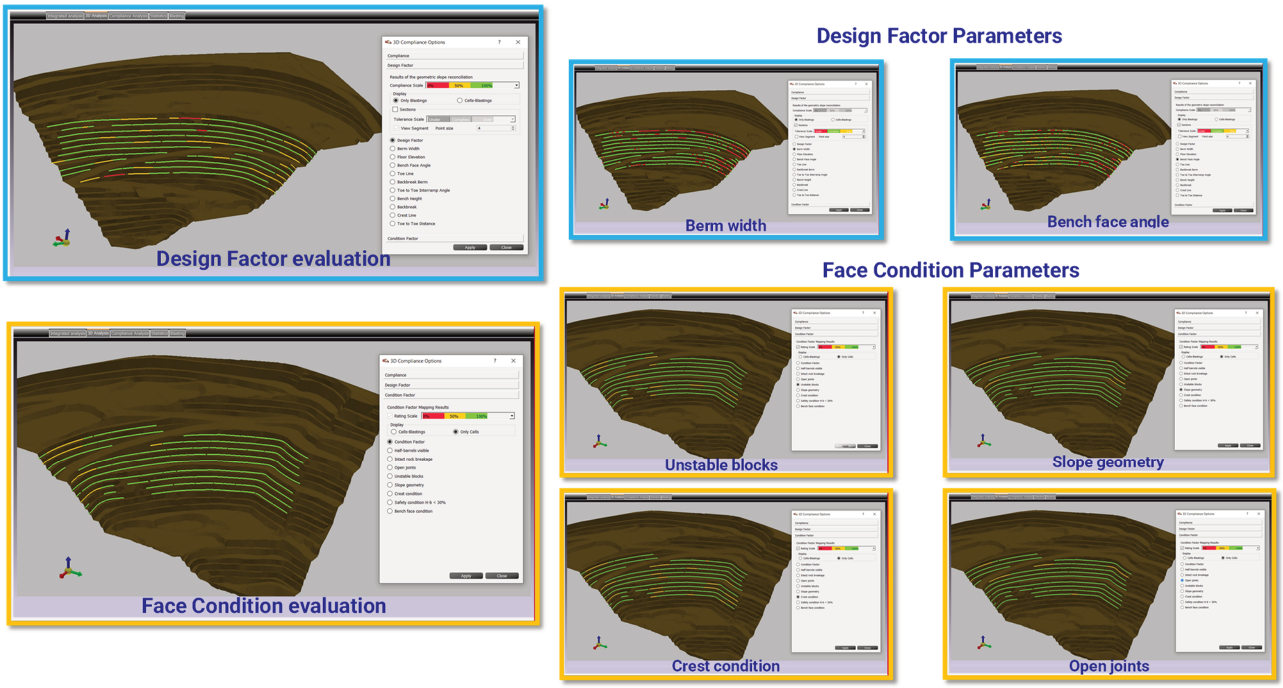


Figure 13 Assessment of bench construction quality. Images captured from TIMining-SICT software

4 Analysis

Criteria for the characterisation of the risk associated with the elements mentioned in the previous section are as follows:

1. Distance to wall:
   a. Far from: the operation cannot be reached by material falling from the wall. This situation reduces the risk.
   b. Close to: the operation is within reach of instabilities and rocks that may fall from the slope. Situation that increases the risk.
2. Containment elements such as parapets and barriers located between the operation and the pit wall:
   a. There are rocks falling from the wall along the entire front of operations which can be contained, decreasing the risk.
   b. There is no or insufficient containment capacity in relation to the material that is not contained by the bench berms.
3. Berms. Depending on the compliance with the design berm width and the spatial distribution of the berms that do not meet the minimum width, two cases are identified:
   a. There is high compliance with the berm width, providing sufficient containment capacity for falling rocks.
   b. There is low berm width compliance, or the benches with low compliance are located in the lower part of the inter-ramp (near the operation); a situation that increases the risk.
4. Vertical phase interference:
   a. There is no phase interference or it is located at a distance greater than one inter-ramp, generating low risk.

b. There is phase interference, with the potential for rock projection, activation of potential instabilities and saturation of berms, which increases the risk.

5. Potential instabilities near the operation:
   a. The loading area is free of potential local instabilities.
   b. There are potential instabilities that could be activated when extracting the material. This situation increases the risk and requires the implementation of adequate loading practices.
6. Active sectors warned by monitoring:
   a. There are no active sectors warned by monitoring.
   b. Presence of a bench–scale active sector.
   c. Presence of an intermediate–scale zone (more than one bench and less than one inter-ramp).
   d. Presence of an overall–scale active zone or larger than one inter-ramp.
7. Saturation of berms:
   a. Clean berms on most of the benches of the inter-ramp.
   b. Mostly saturated berms, especially in the lower part of the inter-ramp.
8. Geotechnical FC of benches:
   a. Most of the benches in the inter-ramp meet the acceptance criteria for geotechnical quality of benches.
   b. The benches of the inter-ramp do not meet the acceptance criteria for geotechnical bench quality, especially in the lower part of the inter-ramp, increasing the risk of rockfall.

5 Results

In this paper, inspired by fault tree analysis (FTA) from the *Guidelines for Open Pit Slope Design* (Read & Stacey 2009), we propose a methodology for characterising the risk (low, medium, and high) to which the daily units of the mining plan are exposed, based on a decision tree constructed from the elements previously described, applied to the vertical section of the wall where the operation is located (drilling or loading) as shown in Figure 14.

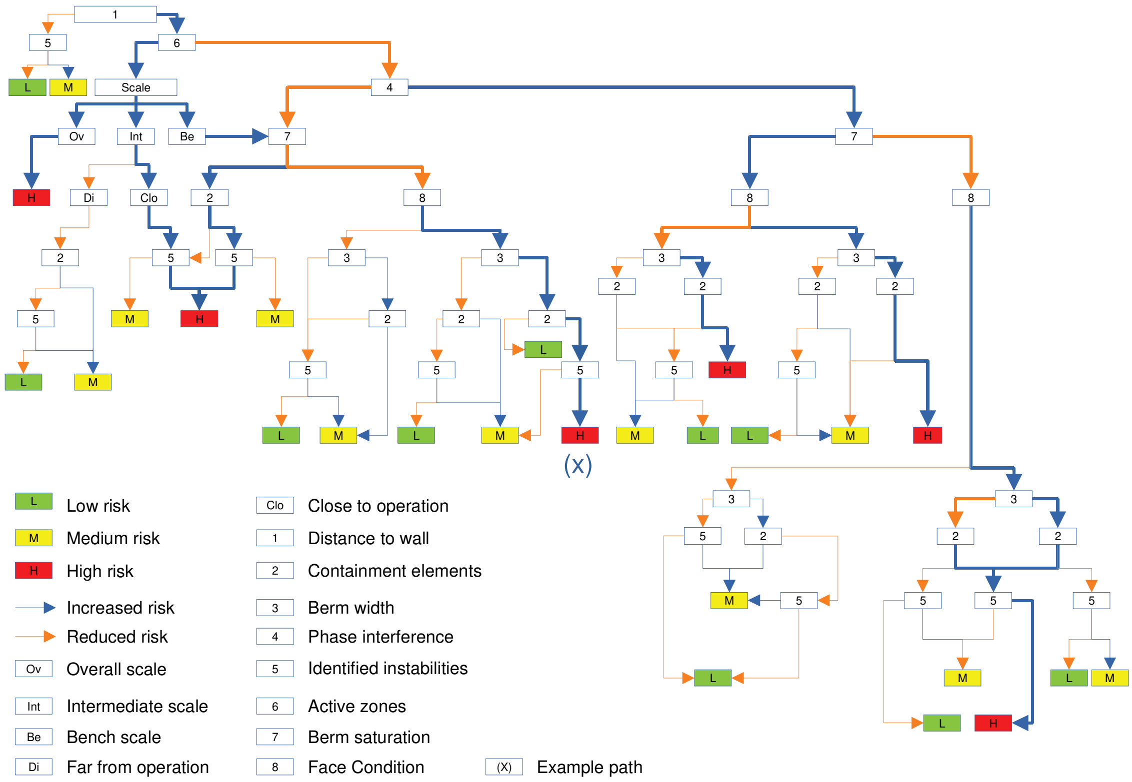


Figure 14 Proposed decision tree for risk assessment of daily units of the mining plan

The paths present in the tree in Figure 14 arise from the combination of the different conditions in which the operation is developed, which may impact the NPV of the project, compromising operational continuity due to accidents to people or equipment, and the use of shovels and trucks in the unplanned hauling and transport of material, as well as delays due to the reconditioning of the production sectors to achieve safe working conditions. Likewise, tree decision paths allow determining measures to mitigate the hazard and lower the risk such as cleaning saturated berms, installing containment barriers, and improving practices to have better results in complying with the berm width and the geotechnical FC.

In the decision tree, the paths that lead to a high-risk assessment are highlighted with thicker lines. As an example, path (X) obtains a high-risk assessment from the following situations:

1. The operation is close to operation (1).
2. No exposure to active sectors warned by geotechnical monitoring (6).
3. No vertical phase interference (4).
4. The berms are not saturated (7).
5. There is a poor evaluation of the FC (8).
6. The berms do not satisfy the design width (3).
7. There are no containment elements to protect the operation from falling rocks from the wall (parapets or barriers) (2).
8. Potential instabilities exist in the operational area (1).

Similarly, in the upper left corner of the tree is a condition worth mentioning. This is an operational area located far enough away from the wall so that it is isolated from rocks that may fall from the slope. In this case, the risk assessment depends only on the identification of potential instabilities in the operational area. If no instabilities have been identified, the risk is estimated to be low. On the contrary, if potential unstable geometries have been identified, the risk will be medium.

Finally, Figure 15 shows a map of the operation with the polygons of the daily units of the weekly mining plan coloured according to the proposed risk scale, which can be correlated with the potential impact on NPV.

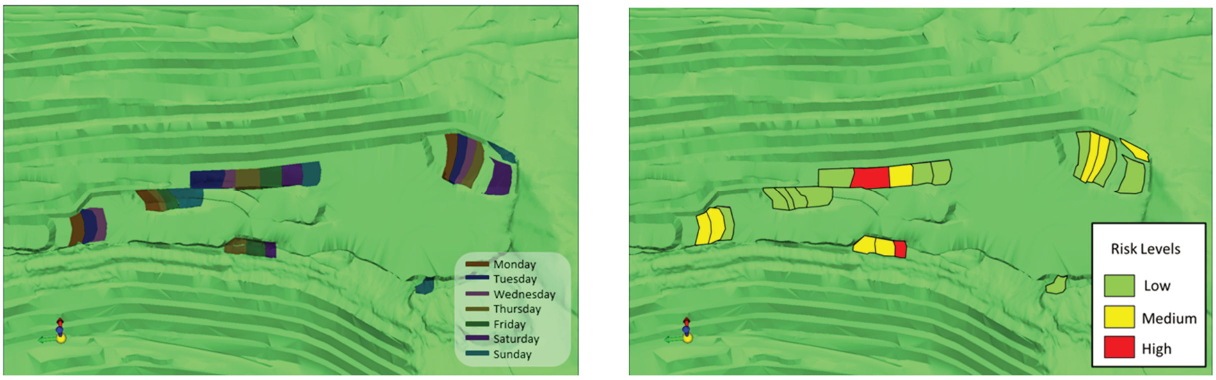


Figure 15 Risk assessment representation of the daily units of the weekly mining plan. Left image captured from TIMining-Delta software (TIMining 2021d)

For the successful implementation of this risk management methodology, it is essential that the operational geomechanics team provide sufficient and quality information from geotechnical monitoring, the reconciliation of the design and constructed geometry, the evaluation of the FC of the benches and the identification of potential instabilities from the projection of structures present in the bench above the operation's development.

6 Conclusion

From what has been presented in this paper, we can draw the following conclusions.

Implementing this methodology allows transmitting situational awareness to the operation, particularly of those hazards associated with operating at distances close to the pit wall.

It is possible to proactively improve the planning and coordination of technological resources and human and mechanical support teams to respond in a timely manner to contingencies that will be faced during each weekly shift, through the geo-referenced visualisation of conditions that could compromise compliance with the mining plan.

A reduction in mining process interruptions is possible, with a consequent improvement in mine productivity, by attending to operational contingencies in a timely manner, based on improvements in prevention, planning and coordination of available resources.

Finally, we can point out that the achievement of batter slopes and compliance with the mining plan, from the use of technologies that facilitate the integration and analysis of geotechnical information, the evaluation of the quality of the construction of the walls (in geometry and condition), risk management, and effective feedback to the operation of the mine and, consequently, an improvement in decision-making will result in objective elements that will allow the company to evaluate optimisations to the pit design, aiming at an increase in economic return, without losing safety or sustainability of the project.

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