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Geomechanical risk management and control at Andes Norte project: El Teniente mine

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Abstract

El Teniente mine expansion plans are currently under development with construction stages through an integrated project strategy that will allow the continuity of future mining. The deepest sector corresponds to Andes Norte project, which has the additional mission of producing new knowledge and experience in deep mining. The project is planned as conventional panel caving with the application of hydraulic fracturing to mitigate the seismic hazard during future mining. It also considers the construction of the definitive material handling system, consisting of a crushing chamber with a capacity of 60,000 tons per day and a 9 km long tunnel to shelter the conveyor belt. This tunnel is currently under construction and the most complex zones have experienced rockbursts.

This article describes the main elements that integrate the geomechanical risk management and control strategy for the Andes Norte Project, addressing risk concepts and strategies, mine design layouts, rock support design and hydraulic fracturing considerations, in addition to the experience gained during its construction and also with El Teniente mine experience applied to this future mining sector.

Keywords: *risk management, risk control, rockburst, hydraulic fracturing, rock support, panel caving*

1 Introduction

The Andes Norte project is the deepest project currently under preparation at El Teniente mine. Its undercutting level is at the average elevation of 1887, approximately 330 m below Esmeralda mine. The total mining polygon has an area of 529,230 m^2, with 375 million tons of resources, at an average grade of 1.02% Cu and a projected mining rate of 35,000 tpd when it reaches its steady-state regime.

The deeper site conditions and the materialisation of geomechanical risks during the construction of the New Mine Level Project (NML Project) caused changes in the mining reserves extraction strategy, adapting mine planning with sectors or projects at different levels. Thus, a mining plan was consolidated based on the Andesita, Diamante and Andes Norte projects, which together integrate the El Teniente mine project portfolio. Andes Norte has the additional mission of generating new knowledge and experience in deep mining for the application of the company's future projects.

In general terms, the Andes Norte project corresponds to a conventional panel caving with the application of hydraulic fracturing both above the undercut level and below the extraction level to mitigate the seismic hazard during future mining. It considers the construction of the definitive material handling system, consisting of a crushing chamber with a capacity of 60,000 tons per day and a 9 km long tunnel to shelter the conveyor belt. This tunnel is currently under construction and the most complex zones have experienced rockbursts. Thus, construction methodologies have had to be adapted to incorporate seismic risk management and control at a tunnel scale. In this sense, the use of technology and mechanisation in the most critical processes have ensured the feasibility of construction in these environments. A general layout is shown in Figure 1.

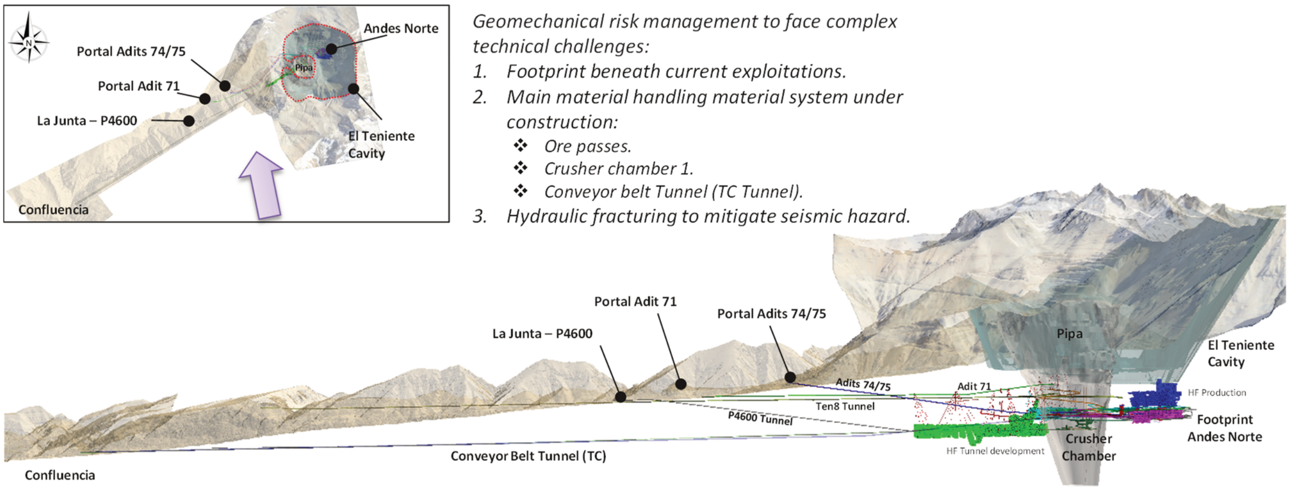


Figure 1 General layout of Andes Norte Project

This article describes the main elements that integrate the geomechanical risk management and control strategy for Andes Norte project, addressing design aspects, experience gained during its construction and also how El Teniente mine experience has been applied to this future mining sector.

2 Geomechanical risk management strategy

In general terms, mining activities create an alteration of the equilibrium conditions of the surrounding rock mass, which tends to a state of re-equilibrium. During this process, deformations and fractures may occur. In the case of primary rock mass environments (high strength and brittle behaviour), under high stress conditions, ruptures can be sudden and the energy released can propagate through the rock in the form of waves, which corresponds to a seismic event.

Seismic events are inherent to the mining process in the primary rock mass, so the preparation and mining considerations and strategies are aimed at managing and controlling the associated risk, in this case, rockburst phenomena. Additionally, in the case of the development and construction stage, mitigation and control actions are also related to wedge falling and overbreak of developments, which are duly included in the rock support design and ground control.

The occurrence of rock bursts at the NML Project, between the years 2013 to 2015, implied significant changes in the way of managing seismic risk at tunnel scale, in comparison to historical experience carried out in developments outside the mining cavity influence. The implemented strategy corresponded to an adaptation of the methodologies used in the mining of El Teniente mine. In this sense, geomechanical risk mitigation and control measures are included in the different stages of the design and mine planning processes along with the construction, being reported under a geomechanics governance scheme, integrated by directors, superintendents and managers of both the El Teniente mine and the Andes Norte project.

From the systemic processes point of view, the first process corresponds to medium- and long-term planning, where the mine production requirements are defined. Then, the mine design is addressed, with emphasis on the design of excavations, construction methodologies, ground support design, expansion of the seismic monitoring network and additional mitigation measures such as preconditioning techniques in the highest risk areas. Then, the development and construction planning stage has a short-term focus and involves the periodic review of development programs, considering the reconciliation of the new available geological, geomechanical and seismic data collected in the field. In this stage, the seismic behaviour of the developments is analysed and evaluated, identifying vulnerabilities that may affect the monthly or quarterly plan, providing recommendations based on the geomechanical environment and geological conditions present in the sectors.

Finally, the construction stage is intended to ensure the implementation of what was defined in the previously described stages, carrying out the capture of geological, geomechanical and seismic information, ground control of the quality of installation of the rock support systems, monitoring of seismicity during shifts and the application of operational controls such as isolation protocols, if applicable. The use of mechanised equipment is also included in this stage as an essential element, representing one of the most important risk control measures, including them in the scaling activities and in the systematic bolt-mesh rock support installation, minimising the personnel exposure to critical areas in both activities.

2.1 Conceptual framework

Uncertainty related to rock mass behaviour must be understood as a main source of hazard in rock mechanics. Depending on the stage of engineering development (i.e. pre-feasibility, feasibility, or construction), risk assessment will be performed through different considerations in terms of mine design, mine planning or operational activities.

Hence, in this section, some definitions about hazard, risk and rockburst risk assessment are described. These are consistent with Codelco's Risk Management Guidelines (Codelco 2012; Rojas & Landeros 2022).

2.1.1 Hazard

Hazard can be defined as an event or condition, of internal or external source and of uncertain occurrence with negative impact. It is divided into two different types: inherent and residual.

2.1.2 Inherent seismic hazard

It is the hazard to which the organisation is exposed to in the absence of controls or actions to reduce its frequency or probability. In this case, it is defined as the maximum seismic response that could be produced by the mining activity. It is evaluated during engineering studies, considering the rock mass characterisation (geological and geomechanical conditions). Uncertainties must be considered in this step.

2.1.3 Residual seismic hazard

It is the residual hazard once the controls or actions to modify (decrease) the inherent risk have been applied. In the case of mining-induced seismicity, the inherent seismic hazard is the one that will be directly related to mining activities after the application of the mitigation measures.

2.1.4 Mitigation actions

Defined actions to reduce the probability of occurrence of hazardous phenomena. In the case of seismic hazard, the most relevant actions are the implementation of preconditioning techniques, rock support designs with higher energy dissipation capacity, operational seismic procedures and mechanised activities.

2.1.5 Excavations vulnerability conditions

Excavations characteristics that make them susceptible to damage from seismic hazard.

2.2 Geomechanical risk assessment

The inherent geomechanical risk is evaluated in the rock mass characterisation stages. In this sense, one of the main sources of hazard for mining designs is the uncertainty of geological, geotechnical and geomechanical information.

Based on the strength and deformation properties of the rock mass, behavioural models are estimated, considering the geometries and excavation sequences of the different mining developments. The result of this stage corresponds to the definition of design and planning considerations and guidelines that allow keeping residual geomechanical risks limited to acceptable levels.

Once the most probable behaviour models have been estimated in the construction and/or operation stages, the purpose is to manage the residual geomechanical risk, creating guidelines and tools for the identification of deviations from the expected geomechanical conditions of the rock mass. Table 1 presents a summary of the main geotechnical and geomechanical risks associated with the different stages of a mining project due to panel caving.

Table 1 Geotechnical and geomechanical risk related to panel caving stages

Development and construction	Caving initiation/steady-state
Rockburst	Rockburst
Wedge falling	Wedge falling (abutment and/or relaxation zone)
Horizontal excavations overbreak	Orepass overbreak
Vertical excavations overbreak	Insufficient caveability
	Subsidence and induced damage to upper levels
	Airblast
	Collapses and pillar failure
	Mudrush

2.3 Caving risk management strategy

For caving scale, where the undercutting blasting, drawbell commissioning and ore extraction from the productive sectors are carried out, the strategy proposed at the El Teniente mine has the purpose of monitoring the cave back geometry because it is the main factor of disturbance around it (Landeros et al. 2012). This work is carried out by a multidisciplinary team, where geomechanical engineering is an active participant in the design, planning and operation of the sectors. The strategy also considers three main aspects: seismic hazard mitigation, damage control and the minimisation of people exposure to sources of hazard (Figure 2).

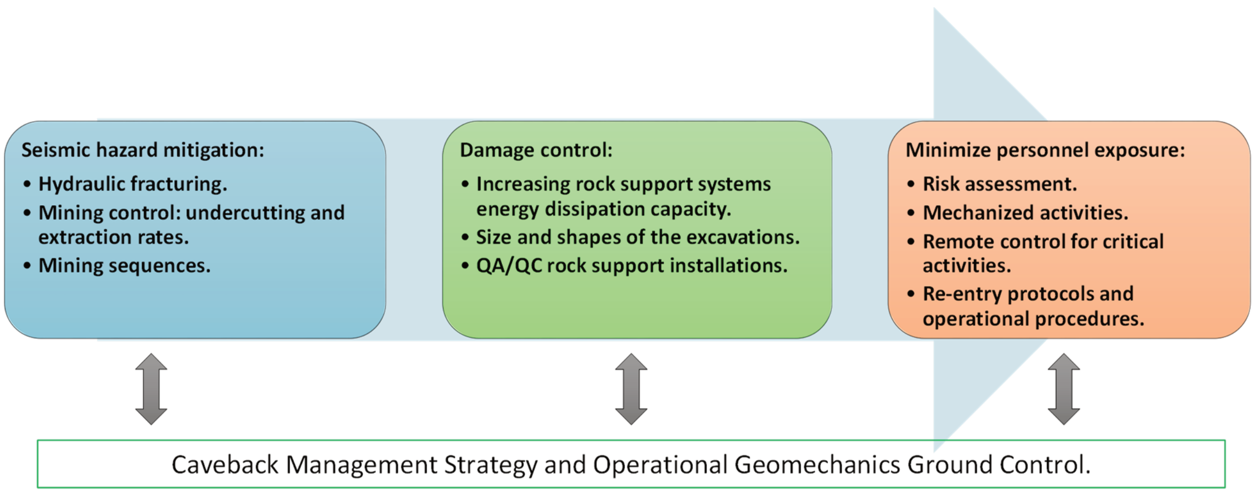


Figure 2 Caving scale seismic risk management

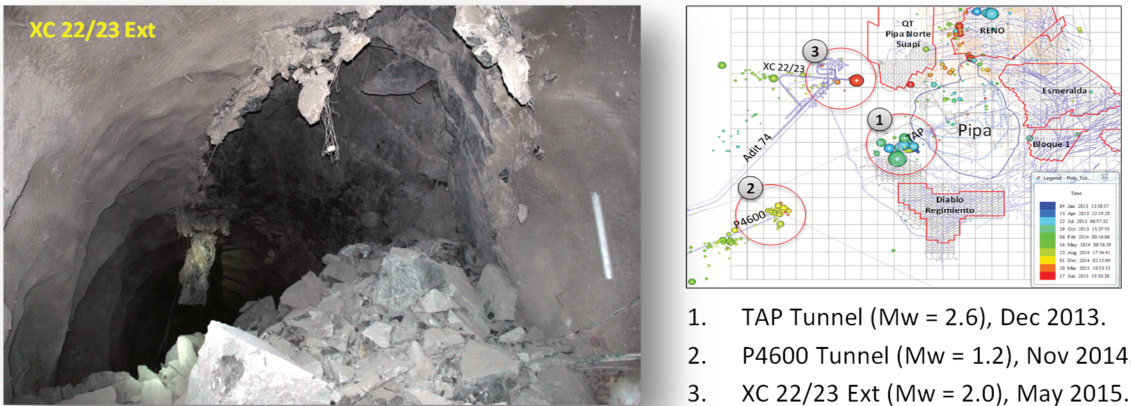
Seismic hazard mitigation, through the implementation of preconditioning techniques such as hydraulic fracturing and confined blasting, which allow to keep ruptures sizes within manageable ranges, directly impacting on the reduction of the recorded events magnitudes. In addition, controls are carried out on subsidence and extraction rates, in order to maintain regularity in the extraction processes and continuity of the caving mechanics. The last aspect of this element is the definition of the mining sequence for the incorporation of area, which represents in practical terms the base geometry of the cavity.

Damage control. This element considers rock mass rupture mechanisms, based on the different dynamic stresses or loads that may affect its behaviour over time. Thus, excavations geometry control and the rock support installation quality assurance of rock support designs allow to reduce uncertainties about the system's installed capacity. Rock support designs have gradually added new elements and new configurations that have increased the systems' energy dissipation capacity. This aspect is considered a fundamental element, given that as projects deepen, the energy released by the rock mass increases in the rupture processes.

Minimisation of people exposure to sources of hazard. This corresponds to the third element of the strategy, in which the identification of zones of greater risk is a main concern, i.e. abutment stress extension around the cavity, with the purpose of performing operational actions such as mechanised or remote activities, allowing to reduce the exposure of people to the sources of hazard as much as possible. In this same sense, there are procedures and protocols for the subsequent re-entry after production and/or undercutting blasting, which are constantly checked by the rock mechanics engineers.

2.4 Tunnelling risk management strategy

As mentioned above, the deepest sector corresponds to the Andes Norte project, which has had to face the rock bursting risk during tunnel construction in a completely different manner since 2013 (Figure 3), implementing different actions for seismic hazard mitigation and seismic risk management, with emphasis on controlling the rock bursting risk with severe or fatal consequences for people.



1. TAP Tunnel (Mw = 2.6), Dec 2013.
2. P4600 Tunnel (Mw = 1.2), Nov 2014.
3. XC 22/23 Ext (Mw = 2.0), May 2015.

Figure 3 Rockbursts during the main infrastructure tunnels development stage, 2013–2015 (Rojas & Landeros 2017)

Main topics regarding to risk management strategy are listed below (Figure 4):

- Definition of an adequate geomechanical governance to support strategic decisions.
- Ground control procedures improvements (geology, geomechanics and QA/QC).
- Implementation of preconditioning techniques such as hydraulic fracturing and de-stress blasting.
- Seismic network locally increasing sensitivity and implementation of operational re-entry protocols.
- Rock support systems improvements, including elements with higher energy dissipation capacity.
- Development rates considerations as a seismic response function (reduced advance lengths, pilot tunnels).
- Implementation of mechanised equipment for more critical activities to reduce personnel exposure.

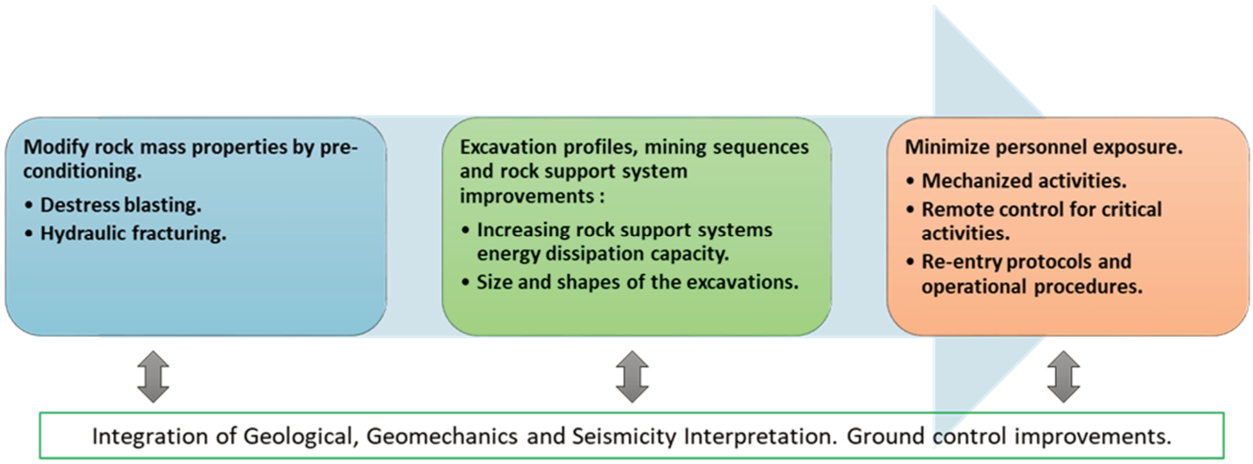


Figure 4 Seismic risk management strategy for tunnelling in high stress environments. Based on hazard evaluations, different aspects may be included into construction methodologies

2.5 Geomechanics governance

Parallel to the construction methodologies technical validation process, organisational structure introduced some changes to allow the proper functioning of decisions associated with geomechanical aspects and their impact evaluations that could directly affect project execution plans. Thus, a Geomechanical Governance structure was implemented with both strategic and operational perspectives, operating at different levels of the organisation.

Within the framework of strategic definitions and decisions, the structure is composed of the Andes Norte project Managers (Engineering, Operational and Portfolio), the Geomechanical Director of El Teniente Division and Andes Norte Geotechnical Director. This team meets weekly to discuss about results and technical geomechanical aspects that strategically impact the project construction plan. The discussion on consultants' recommendations and their applicability is also addressed in this instance.

On the other hand, within the framework of operative decisions, the structure is composed by the Andes Norte project operative manager, construction directors and heads of construction, geology and geomechanics departments. This team meets weekly to carry out the operational follow-up of construction activities with emphasis on ensuring the correct application of controls, operational protocols and mitigation actions to keep the operational risk limited to the design definitions. Both decision-making bodies have been key to assure traceability of the phenomena and associated impacts, maintaining fluent communication between the teams and project stakeholders.

3 Footprint design

3.1 Geological and geotechnical conditions

Andes Norte project is fully located in primary rock mass, where the largest volume corresponds to El Teniente Mafic Complex (CMET), which represents about 85% of the in situ material to be mined. The dioritic Porphyry (PDI), which is located in the northwestern and southern part of this polygon that represents 9% of the in situ material to be mined. The anhydrite breccia is preferentially developed at the contacts of the porphyries that intrude the CMET, and it represents 2% of the in situ material. The porphyry dioritic and porphyry igneous breccia (BXIPDI) is found in the contact between the CMET and PDI, representing 3% of the material and 1% of other rock types. In Figure 5, it is possible to observe the main geological features.

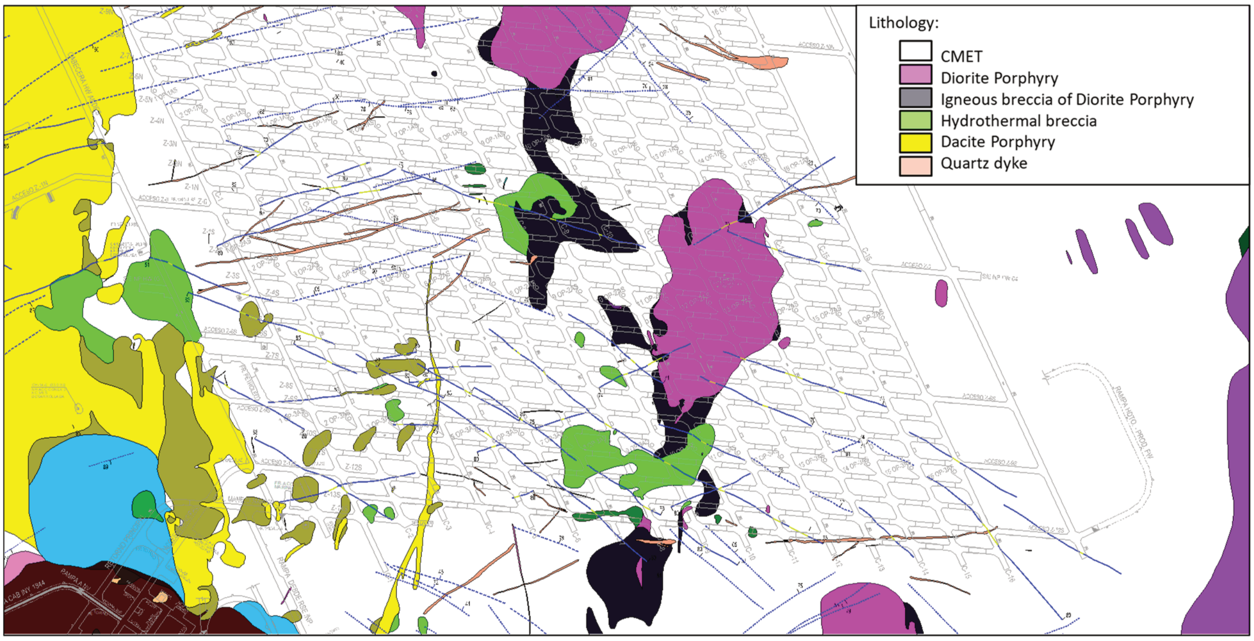


Figure 5 Geological main features and extraction level layout (modified from Celhay, 2016; Padilla & Ferrada 2018)

3.2 Pre-mining stress state

Andes Norte project mining sector is located below Esmeralda, Pilar Norte and Reservas Norte mines, where their current cavities influence the pre-mining stress state. Increasing magnitudes are also consistent with the deepening.

In order to improve the understanding of pre-mining stress, the El Teniente mine-scale numerical model was extended in depth. This model represents results from an iterative process, including calibrations against damage conditions, stress measurements, hydraulic fracturing pressures, overbreaking and seismicity. Average principal stress magnitudes and orientations are described in Table 2.

Table 2 Pre-mining principal stresses magnitudes (Balboa et al. 2017)

Principal stress	Magnitude (MPa)	Azimuth (°)	Plunge (°)
Major – S1	55–60	305–325	7–15
Intermediate – S2	40–46	34–52	5–30
Minor – S3	25–32	Sub-vertical	

3.3 Mining method: Conventional panel caving with hydraulic fracturing

As described by Pardo & Rojas (2016), the NML Project initially considered the use of panel caving with a crinkle cut advanced undercutting strategy. At the same time, promising results on the hydraulic fracturing application to mitigate seismic hazards at different mines of El Teniente, in addition to the operational flexibility that could be reached with post-cut sequence, finally supported the decision to select conventional undercutting as the mining method.

Some specific design considerations were carried out in order to increase both the extraction level pillars' and crown pillars' strength. Also, some improvements from El Teniente mine experience were included into Andes Norte designs such as hydraulic fracturing (HF) drill holes on the polygon boundary to assist the caving process. Results from tunnelling inside HF volumes have been very useful to design properly and for assessing designs alternatives. In Figure 6, a schematic view of Andes Norte mining levels is shown. Hydraulic fracturing design will be explained in detail in the following sections.

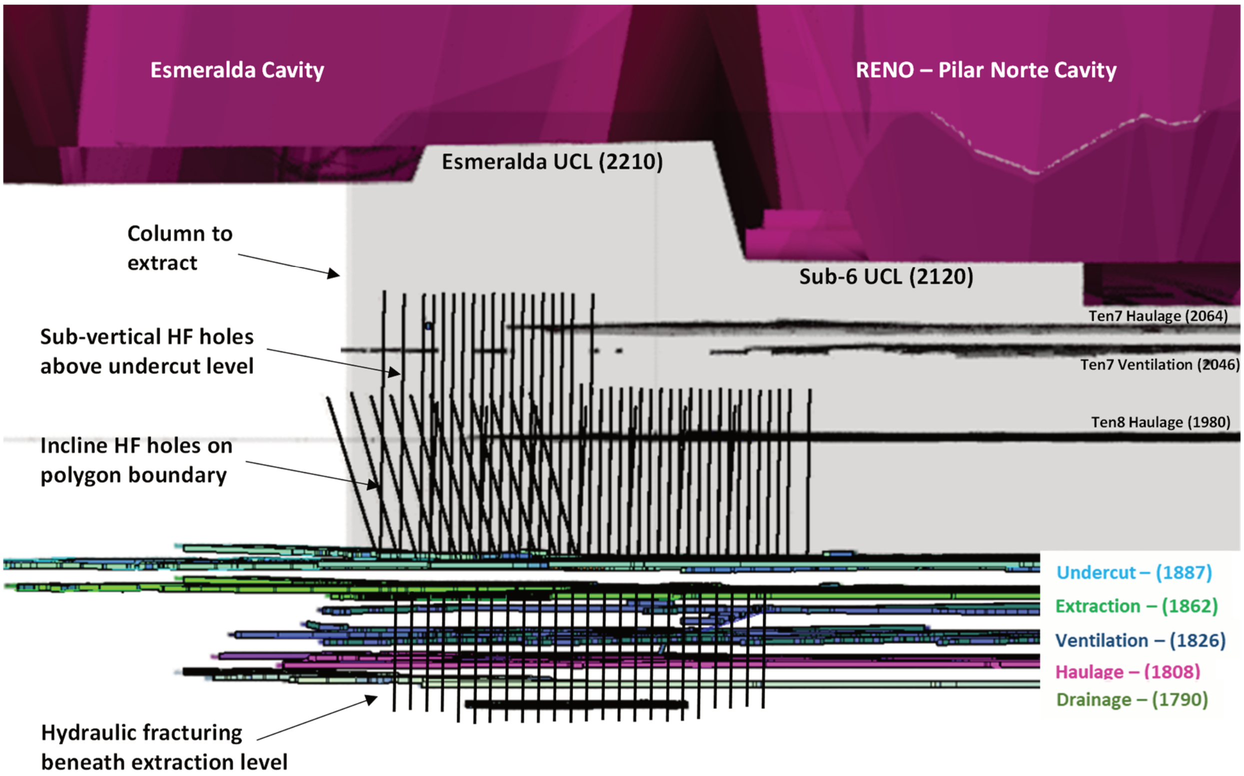


Figure 6 Andes Norte Project schematic view with levels elevations and configuration around current mining sectors, in addition to the HF design performed prior caving initiation

3.4 Mine layouts

Andes Norte project considers five main levels inside the mining polygon, as shown in Table 3.

Table 3 Level elevations in comparison to UCL

Level ID	UCL	Extraction	Ventilation	Haulage	Drainage
Mine elevation	1887	1862	1826	1808	1790
Relative distance to UCL	–	25 m	61 m	79 m	97 m

Relative distances to the undercutting level were increased in comparison to current mining activities in order to improve stability conditions, reducing excavations vulnerabilities once the abutment stress zone reaches different places. Another important design consideration is the extraction level pillar dimensions, because extraction drifts distance is set to 34 m and drawbells distance is set to 22 m. Both situations are schematically shown in Figure 7.

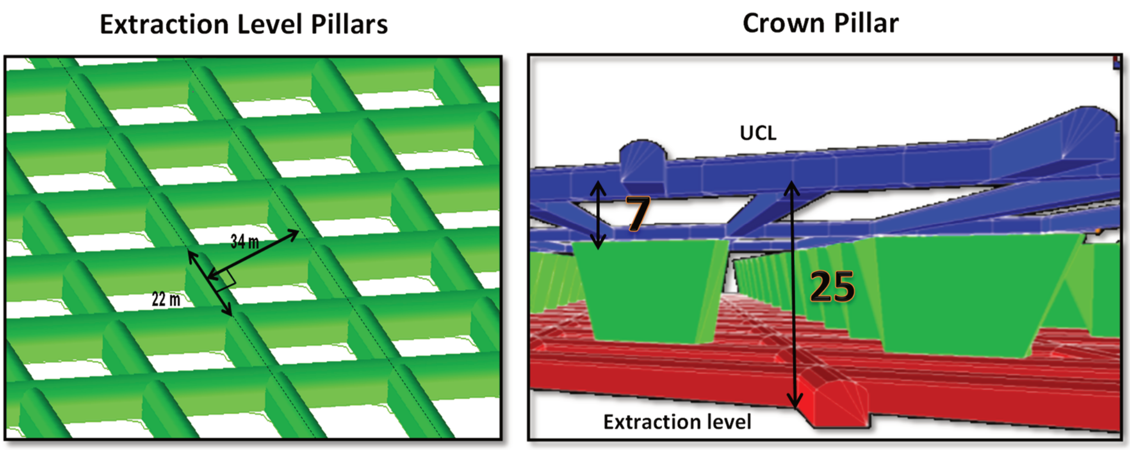


Figure 7 Extraction level configuration scheme and crown pillar dimensions (Rojas et al. 2016)

3.5 Mine development and construction sequences

During early developments, in March 2016, a rockburst occurred due to the interaction between two excavations, which was triggered close in time between the ventilation and haulage levels. After that situation, a specific procedure was established with re-entry protocols and geomechanical considerations that were implemented to mitigate interaction potentials. Also, ventilation crosscut (XC) positions were modified to prevent future interactions. Currently, there is a periodic review of development plans, based on a methodology for risk assessment by the identification of more vulnerable zones, considering rock mass conditions (geological features, pre-mining stresses and hydraulic fracturing) in comparison with excavation span and historical recorded seismicity. The methodology integrates the information and it creates a vulnerability map as a guideline for the geomechanics engineer to improve assessments and priorities to follow-up. In Figure 8, a flow chart is shown with the main subjects. Another matter that must be assessed during the plan review is related to potential interactions between different faces. In that case, a warning is described to construction engineers to be aware about it.

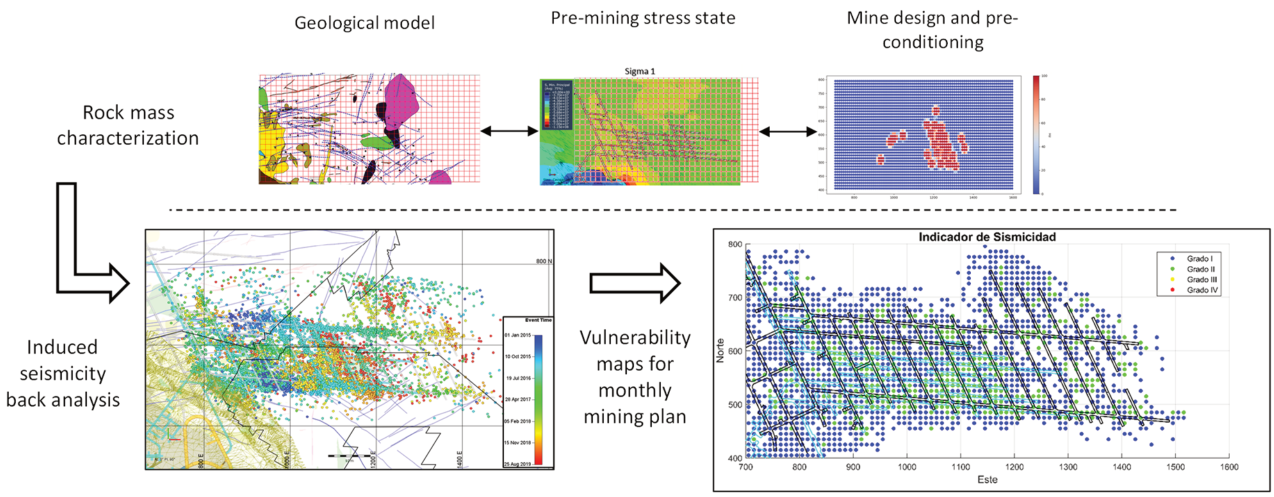


Figure 8 Evaluation of seismic vulnerability during the construction stage. It considers a back-analysis stage for periodical estimations, relating rock mass conditions, mine designs and seismicity induced by developments (Romero et al. 2019)

Finally, all the blasts performed during the shift are reported to a seismic operator, who is in charge of looking each one of them on the system and manually process the signals. This control has been very useful to allow the early identification of seismic events hidden during the blasting seismogram recording.

4 Rock support design and considerations

4.1 Background and designs evolution

The process of rock support design under high stress conditions requires an understanding of the dynamic failure mechanism of both rock mass and rock support systems. Based on the experience of El Teniente mine, rockburst back analyses have been performed in recent years to estimate the energy demands, resulting in a reliable database of cases. These values are the basis for estimating how much energy the system could dissipate during dynamic loading. This situation motivated a complete elements characterisation used for the different systems. The relevant characteristics are basically the energy dissipation capacity, deformation capacity and corrosion strength (Muñoz et al. 2016).

Each rockburst is investigated in detail by rock mechanics teams, addressing both the rupture mechanisms associated with the seismic event as well as the dynamic stress mechanism applied on the rock support system. The experience of El Teniente mine has allowed the inclusion of new elements and criteria, as can be seen in the following chart (Figure 9).

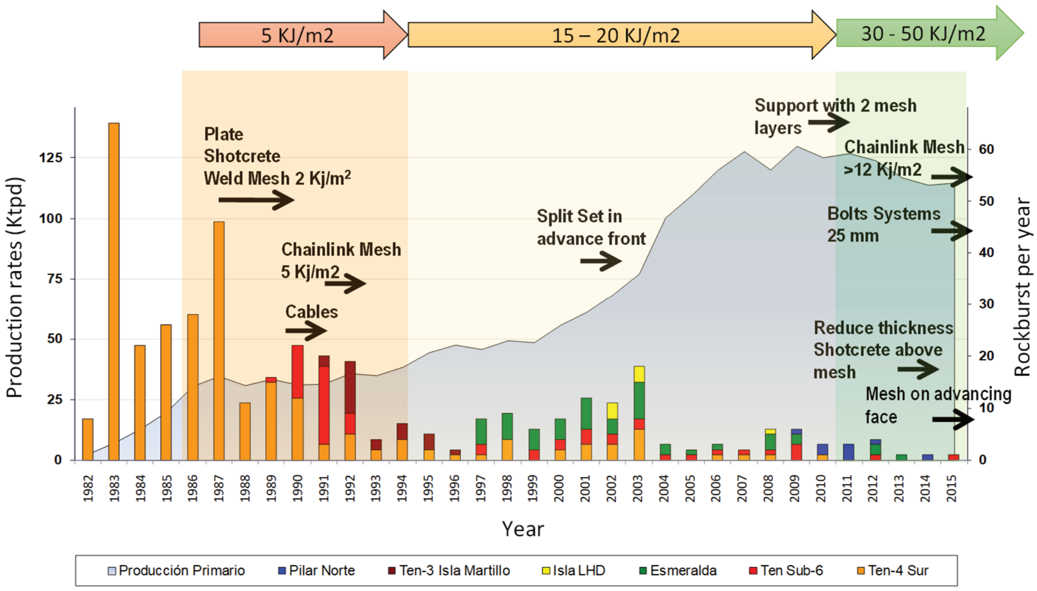


Figure 9 Rock support systems evolution in comparison to El Teniente mine production (Muñoz & Rojas 2016)

4.2 Conceptual approach

The design methodology considers static and dynamic requirements evaluations of the different zones, installing systems sequentially. There are zones of low to moderate seismic hazard, where the rock support system considers only one layer of elements, such as the bolt-mesh-shotcrete system. In other areas, where the seismic hazard is higher, the systems are composed of combinations of elements to increase strength and capacity, such as the bolt-mesh-shotcrete system with cable-mesh as the second and final layer. It should be noted that the characteristics of each element also play a role in the final capacity of the system, such as the types of steel and their mechanical properties (strength, deformability and ductility).

The interaction between each element of the system is a major concern. The way load is transferred between bars, plates and nuts along with their interaction with retaining elements such as mesh and shotcrete is something that cannot be considered individually. Thus, rock support designs follow a system's concept that works in an integrated manner once the rock mass is dynamically loaded during a large seismic event.

In the example shown in Figure 10, the rock support design is defined by two layers: rockbolt, mesh and shotcrete, and then a second layer of bolt and mesh is installed to increase the system capacity. It is possible to see how the collaborative system works when it is properly installed, fully retaining the rock mass failure after a seismic event. Under this situation, the installed system fulfils its design function and it is not possible to determine its remaining capacity, so, the full design capacity must be restored by installing new elements by operational rehabilitation.

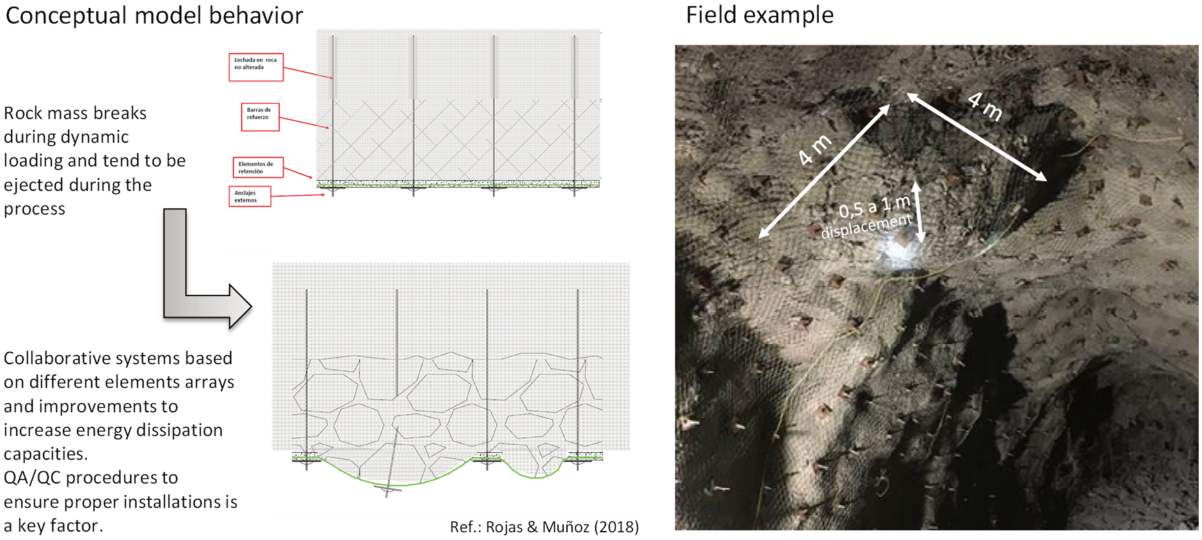


Figure 10 Rock support behaviour during dynamic loading. Conceptual model in comparison to tunnel response after a large seismic event (modified from Muñoz 2019)

4.3 Improvements from El Teniente mine experience

The thickness of the shotcrete layer that covers the mesh is another important aspect to consider in the design of the rock support system and, subsequently, ground control engineers must consider to carry out an adequate control of its implementation. The mesh requires a thin film of shotcrete to protect it from the operational condition, but under dynamic terms, a thicker shotcrete layer over the mesh will create a hazardous condition known as 'shotcrete rain'. The experience of El Teniente mine indicates that a thicker shotcrete layer over the mesh must be prevented; in some cases, it is possible to identify zones with significant deviations, so, the potential installation of a second mesh with shorter rockbolts must be considered as a corrective action to mitigate the effect. Some examples are shown in Figure 11.

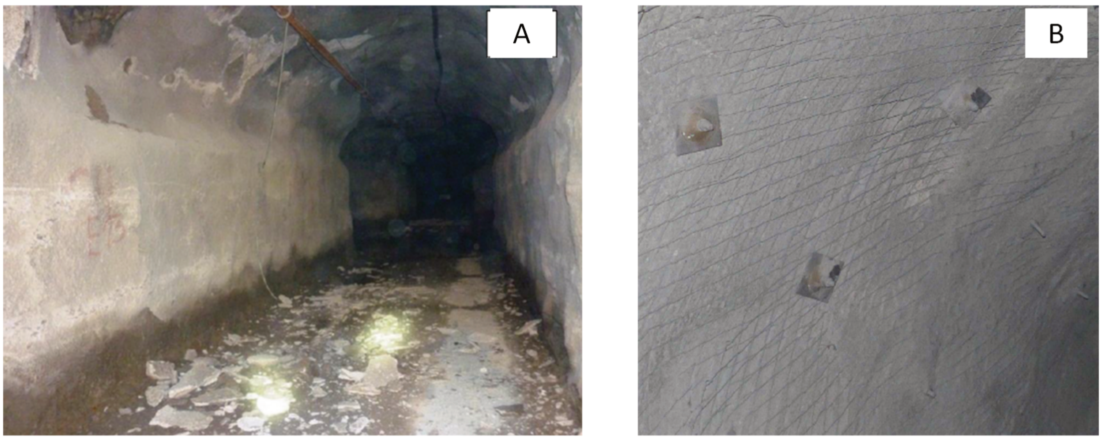


Figure 11 In (A), shotcrete slabs on the floor after a dynamic loading due to a large seismic event at Pilar Norte Mine (Parraguez 2011). In (B), current rockbolt, mesh and shotcrete system design properly installed with a thin shotcrete layer over the mesh for hazard mitigation

Another important design consideration corresponds to the support face stability. In high stress environments, small cracks around the excavations could take place during mining cycle, depending on excavations profiles and geotechnical conditions. Then, the final geometry between the back and the face has to be assessed from the design point of view and not only from the operational perspective. The most critical activity at the advancing face is the next blast charging and firing configuration. In addition to preventive seismic evacuation procedures at higher risk zones (i.e. noise and/or popping identification), rock support design considers a temporary system such as mesh with split sets bolts (or short grouted bolts, depending on the case) to be installed on the tunnel face prior miners perform those activities, as shown in Figure 12.

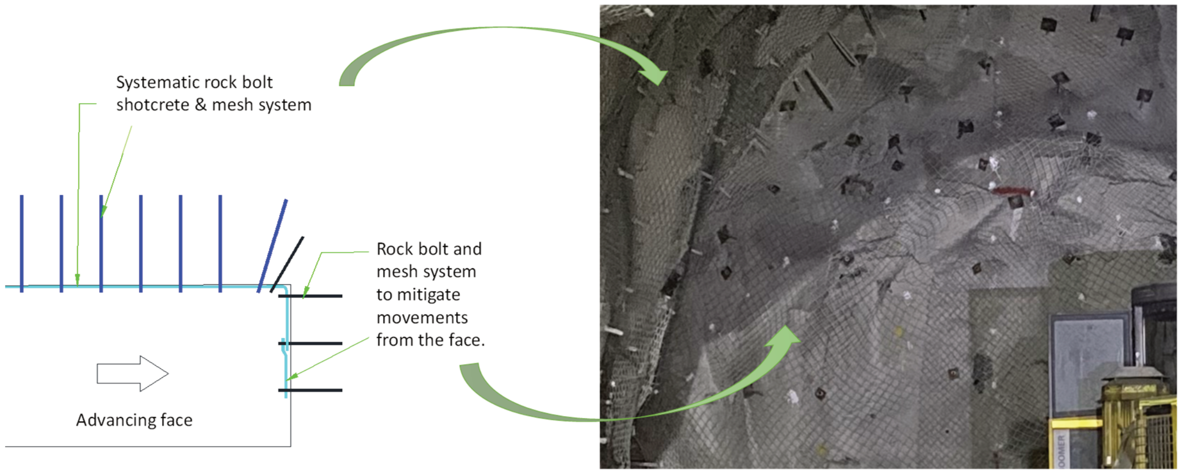


Figure 12 Configuration scheme of systematic rock support system installation around the tunnel profile in addition to the installed system on the advancing face. The interface between both systems must necessarily consider overbreaking and it could be adjusted, according to ground control conditions

4.4 Vertical excavations

Due to high stress conditions, conditioned not only by higher major principal stress magnitudes (sub-horizontal) but also by higher anisotropy levels, vertical excavations are an important concern in terms of stability during life-of-mine period. Experience from Andes Norte development stage has motivated the geotechnical teams to improve the characterisation procedures with focus on the early identification of potential vulnerability conditions. In Figure 13, it is possible to observe different borehole indicators which are later integrated to rock mass response to tunnelling.

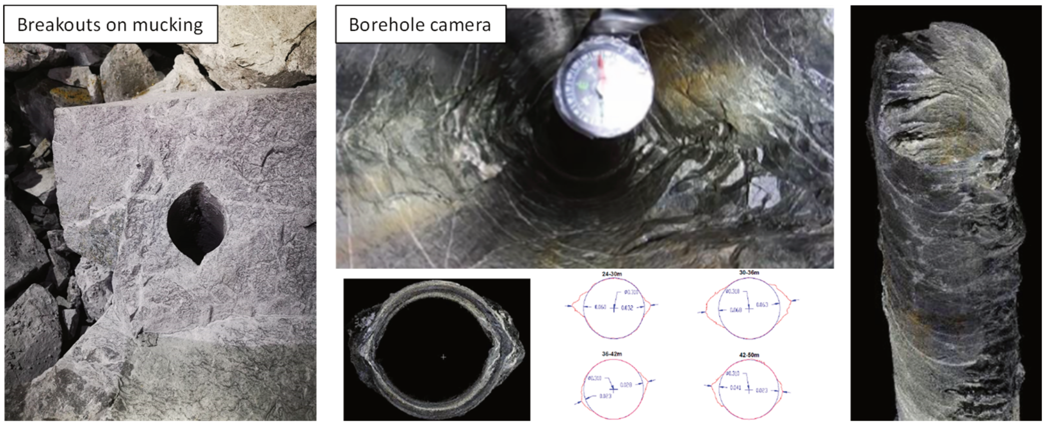


Figure 13 Different indicators of high anisotropy stress at borehole scale (Rodríguez 2019; Moraga 2018)

Then, risk management and control decisions have tended to face this hazard from two different approaches: with the inclusion of steel liners for ventilation shafts and the full mechanisation of ore passes construction methodologies. A schematic example of ventilation shafts is shown in Figure 14.

Figure 14 Ventilation shaft overbreak. Steel liners installation process to control future instability (Madrid 2020)

5 Hydraulic fracturing

Hydraulic fracturing at Andes Norte project has been conceived as a way to mitigate seismic hazard both during the caving process and tunnelling in high stress environments. In Figure 15, a schematic view of fracturing zones is shown. Activities related to fracturing for tunnel developments are already completed, currently concentrating efforts for the caving process.

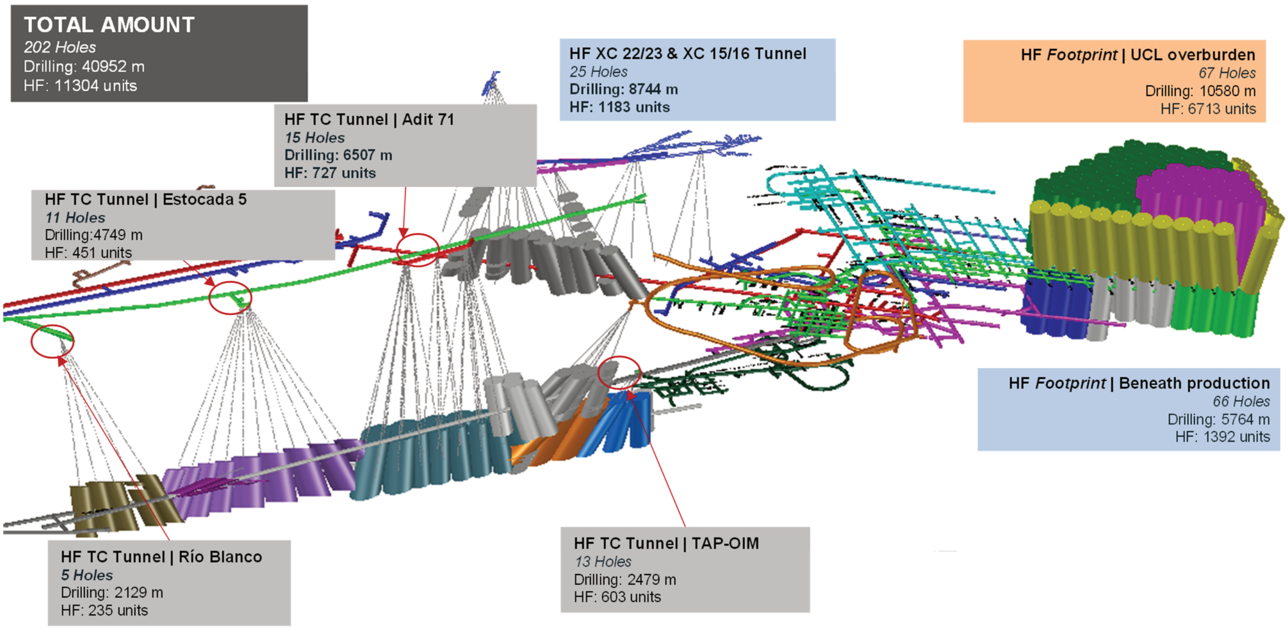


Figure 15 Defined hydraulic fracturing volumes for Andes Norte Project initial stage. It considers HF for caving mining (footprint) and for tunnelling developments in high stress conditions

5.1 Design guidelines and considerations

In general terms, the current practice of El Teniente mine considers two stages for hydraulic fracturing design process: borehole design and fracturing operative process considerations. Each stage defines different parameters and key factors that may condition the hydraulic fracturing application performance. A summary is presented in Table 4.

Table 4 Hydraulic fracturing design parameters and considerations

Design step	Design parameter	Key factor
Borehole design	Collar position	Available locations (i.e. excavations) Estimated radius of influence Mine services and potential rehab requirements Additional excavations requirements in case of no available access
	Borehole orientations	Minor principal stress direction
	Borehole lengths	Rock mass volume to be fractured
Fracturing considerations	Injection position	Rock mass volume to be fractured Operative excavations near to injection points
	Injection time	Required radius of influence Rock type
	Fractures spacing	Angle between borehole and minor principal stress direction
	Injection sequence	Potential straddle packer damage
	Isolation protocol	High pressure lines Near excavations and seismic hazard
	Maximum pressure	Rock type and strength Estimated breaking pressure

5.2 Extension and morphology trials

Andes Norte project considered the utilisation of new injection pumps for the hydraulic fracturing process, representing an upgrade to El Teniente mine traditional application in terms of breaking pressures and increasing injection rates. As these parameters condition propagation results and performance, a specific trial was considered to evaluate the need of some design adjustments prior their massive execution (Figure 16).

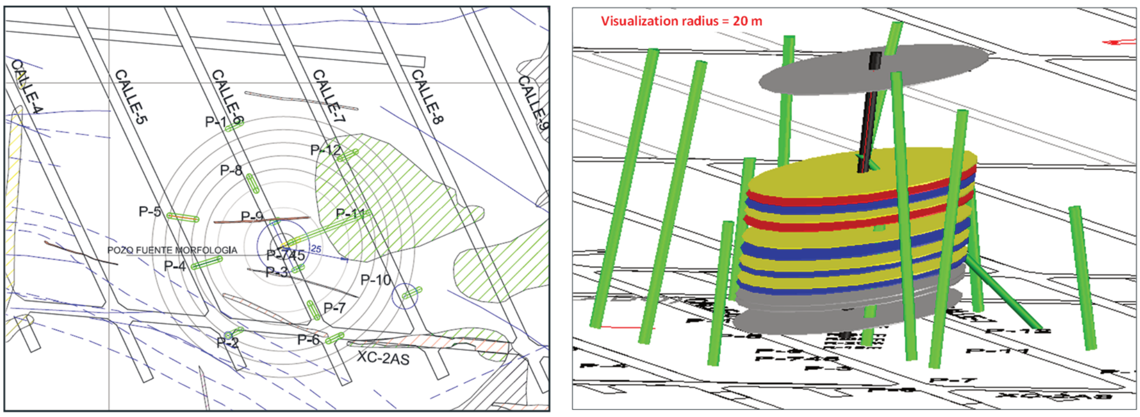


Figure 16 Hydraulic fracturing trial configuration to assess fractures extension and injection rates (Barahona & Pardo 2017)

A trial operative configuration considered fracturing one borehole outside any previous disturbance was considered. This hole was located at the undercutting level, upwards, with CMET as principal lithology. Colored inks were used in addition to water and 12 monitoring holes were included to monitor water extension. Additional holes were drilled after injecting with the expectation of being able to map them at that scale. Main results at that stage validated the fracturing process under Andes Norte environment and ink identification supported a better understanding of the HF effect on the rock mass.

Furthermore, maybe the most important conclusion was related to higher injection rates. In that case, water propagation was monitored with larger extensions and finally, the hydraulic fracturing design was optimised while using a similar pumps configuration (Table 5).

Table 5 Hydraulic fracturing radius for design purposes, based on injection rates and pump types (modified from Cifuentes et al. 2019)

ID config.	Nominal injection rate	Max. injection pressure	Extension radius
Type 1	310 (lt/min)	55 MPa	20 m
Type 2	380 (lt/min)	77 MPa	30 m

5.3 Hydraulic fracturing current design

After extension and morphology trial results, the following step was to optimise hydraulic fracturing designs. In the case of the volume to be fractured above the undercutting level, three different zones were defined as follows (Figure 17).

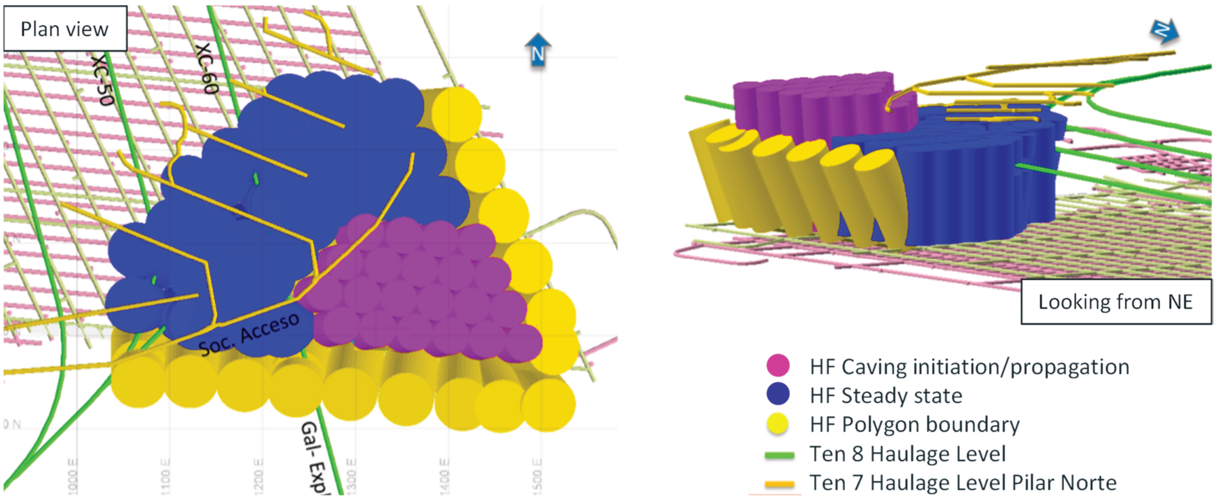


Figure 17 Defined hydraulic fracturing volumes for Andes Norte Project initial stage. It considers HF for caving mining (Footprint) and for tunnelling developments in high stress conditions (Cifuentes & Arce 2020)

Caving initiation and propagation: This zone remains with no variation in order to avoid generating singularities between fractures that could induce design singularities that could affect caving propagation. The design radius was defined in 20 m with sub-vertical holes, 30 minutes of injection time and 1.5 m for fracture spacing.

Steady-state regime: This zone was modified in height to prevent the interaction with upper levels and also design radius considered trials results (30 m), with sub-vertical holes, 30 minutes of injection time and 1.5 m for fracture spacing.

Mining boundary polygon: The main purpose of this zone is to mitigate seismic hazard around the cavity boundary and helping confined geometries to propagate. Boreholes were adjusted to prevent interactions with upper levels. The design radius was defined in 30 m, inclinations between 65° and 73°, 30 minutes of injection and 2.0 m for fracture separation.

The hydraulic fracturing design for beneath the extraction level volume remained with less variations because most of the fractures were already performed at the time of trial results.

6 Conclusion

El Teniente mine expansion plans are currently under development and construction stages through an integrated project strategy that will allow the continuity of future mining. The deepest sector corresponds to Andes Norte project, which has the additional mission of creating new knowledge and experience in deep mining.

An integral geomechanical risk management and control strategy has been defined with an adequate Geomechanics Governance to support decisions. This strategy is essentially based on risk concepts and the analysis of rock mass response to mining, considering two different scales: tunnelling and caving.

In the case of tunnelling, main elements involve improvements on ground control procedures, rock support systems, mining sequences and seismic network sensitivity; on the other hand, the implementation of preconditioning techniques jointly with mechanised equipment for the most critical activities. Mechanisation have been a big successful challenge not only for geotechnical and construction teams but also for the whole organisation.

In the case of the caving scale, the integration with El Teniente mine experience has been a key factor, including definitions for the mining method, seismic hazard mitigation by rock mass preconditioning and cave back management strategies such as mining sequences and extraction rates. New rock support elements, the experience gained during the last 35 years with primary rock mass mining and lessons learned from collapses and rockburst back-analysis have supported the Andes Norte design layouts and the future operational philosophy, looking forward to include the best current practices.

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