

Post-evaluation macroblock N1/S1 exploitation, Chuquicamata underground mine

S. López N., G. Barindelli P. and J. Videla W.

Codelco Chile – División Chuquicamata

ABSTRACT

The Chuquicamata Mine began operations in April 2019, transitioning from a purely open pit operation to a mixed pit-underground operation between 2019 and 2022, eventually becoming fully underground. From 2022 onwards, the primary goal has been to achieve a Ramp Up to 140 ktpd over the next seven years. During 2020, the progression and closure of the incorporated area from the macroblock N1/S1 led to six collapses in the productive area. A thorough study was conducted on the main issues related to stability problems, including mining design, mining exploitation behavior, drilling, blasting, causality analyses, and categorization analyses of various aspects. This comprehensive study enabled the identification of the main causes of stability problems. The primary cause is linked to the design of the pillars at the edge of stability. The rock mass, which is of regular and poor geotechnical condition and has a high overbreak in the drift of the production level (averaging 22%), resulted in 50% of the pillars being in a borderline condition. This particular situation necessitated a high level of excellence in the development, construction, and exploitation of the operational area. The condition of the pillars worsened due to various contributing factors, leading to a percentage analysis that determined the contribution grade (weight) of each parameter in the stability problems.

1 INTRODUCTION

Starting from April 2019, the Chuquicamata mine underwent a transformation in its exploitation method, transitioning from a 100% open pit operation to a mixed pit-underground operation, and ultimately becoming a fully underground operation. The exploitation method was defined by the project as Block Caving.

In July 2020, after the advancement and incorporation of the underground mine area, instabilities of the collapse-type occurred in some areas of the production level streets. This situation persisted even after the closure of the central macroblock N1/S1 in October 2020.

Although it affected some draw bell lines on drifts 4 South (East-West), 1 North (Center), 3 South (East) and 3 North (East-West), it resulted in the cessation of total production on drifts 4 South and 3 North.

This report analyzes the background related to the progress and growth of the incorporation of area and caving propagation of the Chuquicamata Underground Mine to determine both the causal hypothesis and the main factors contributing to the registered instabilities in the drifts of the production level.

2 OBJETIVES AND SCOPE

The objectives and scope of this study are as follows:

- Analyze the available background information up to date, regarding the design, implementation, operation, and growth of the exploitation of the Chuquicamata Underground Mine to determine the factors that could influence the occurrence of instabilities (collapses) in the production level.

- Define and validate the causal hypothesis of the occurrence of damage (instabilities) in the drifts of the production level.
- Determine and analyze the main factors (design, implementation, operation, etc.) contributing to the occurrence of instabilities in the Chuquicamata Underground Mine.
- The scope of this report includes the analysis and evaluation of all the information and background related to the development, advancement, implementation, and operation of the N1/S1 macroblock for the period 2019-2020.

3 HYPOTHESIS

The advancement of the incorporation of the Macro Block N1/S1 area led to 6 collapses of the productive area. The main cause is hypothesized to be associated with a design of pillars in a condition of stability at the limit, in a rock mass of regular to poor geotechnical quality. With a high overbreak in the galleries of the production level (on average 22%), it resulted in 50% of the pillars remaining in a limit condition, requiring a high level of discipline in preparation (development and construction) and operation (incorporation of area and extraction).

4 BACKGROUND

The following chapters provide analyses of each aspect that was part of the analysis of the stability problems of the N1/S1 macroblock of Chuquicamata Underground.

4.1 Geology & Geotechnic

This chapter presents the basic geological and geotechnical information of the deposit, providing an overview of the different alteration and mineralization processes that led to the formation of the Chuquicamata mine.

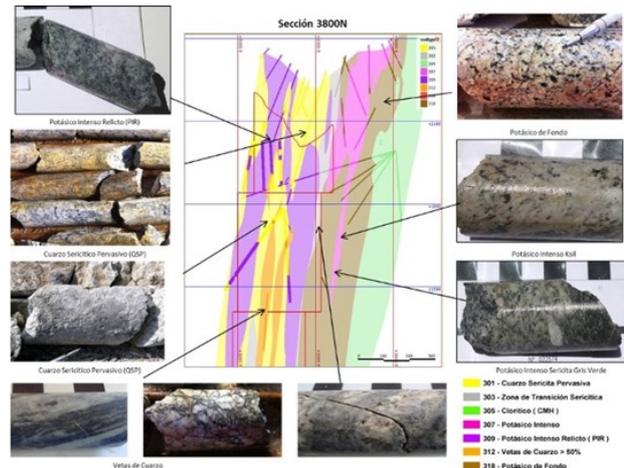


Figure 1 Section W-E Alteration Model Macro blocks N1/S1, in Chuquicamata Underground.

The central macroblocks are predominantly situated in the Quartz – Sericitic zone, which is subdivided into three units for the purpose of understanding its genesis and the distribution of Copper (Cu). These units, defined based on varying degrees of alteration and mineralization (Vásquez et al, 2023), are referred to as PEK (Potassic), PES (Sericitic), and RQS (Quartz Sericitic). The RQS unit is further divided into QIS (Q=S), QMES (Q <S), and QMS (Q > S) based on the quartz-sericite content.

The mine provided the rock mass strength properties in terms of standard rock mass parameters (density, σ_{ci} , GSI, and m_i) for each unit, including the Americana Fault Zone (AFZ).

The geotechnical-structural model aligns with the geological models, with the American Fault being a notable feature. This fault, which limits the alteration and mineralization units, is characterized as a fault zone with a North-South orientation composed of several branches, each approximately 40 m wide.

Another significant fault system is the NW system, which consists of multiple branches. The NE structural system is also noteworthy, with well-defined faults spaced between 30 and 50 m apart. These are depicted in Figure 2.

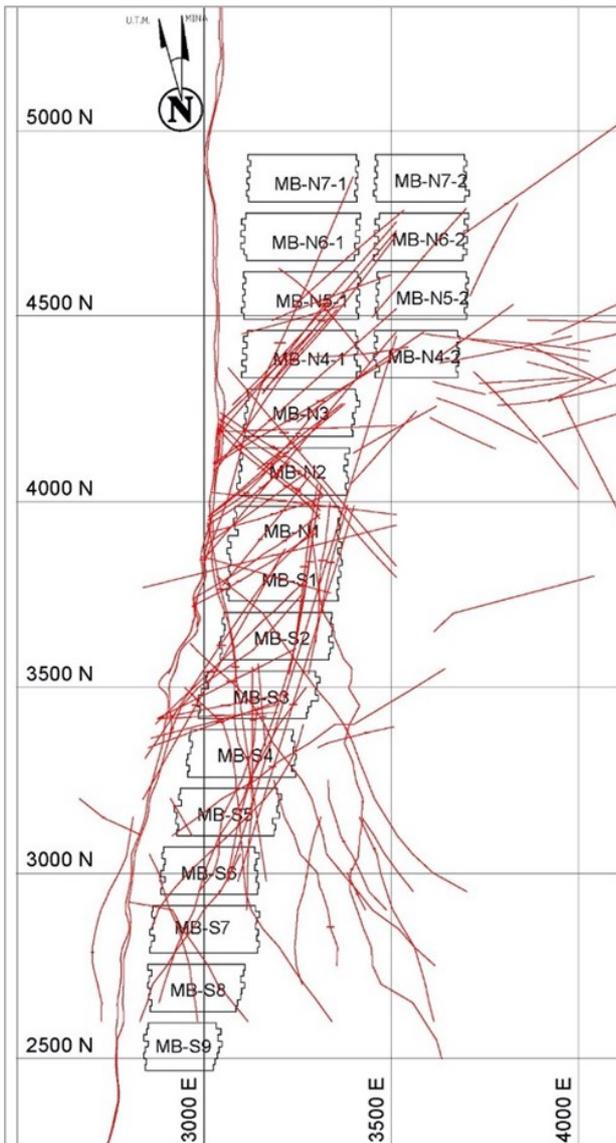


Figure 2 Production Level Structural Model, Chuquicamata Underground.

4.2 Stress Field

The stress model update takes into account the historical data of stress measurements conducted up until 2015. This data was used to ascertain the current stress field in the underground mine. The results are summarized below. Additionally, a detailed analysis of the effort measurement campaign, undertaken by the Chuquicamata division between 2018 and 2020, is also provided. These elements are depicted in Figure 3 below:

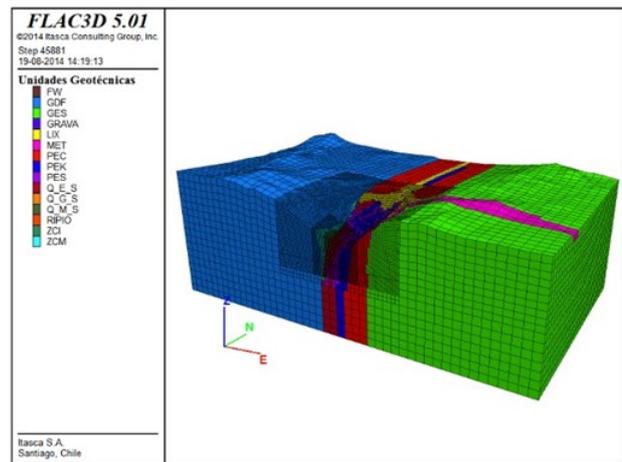


Figure 3 Stress Calibration Model with FLAC3D, Chuquicamata Underground.

The stress calibration results (Itasca 2015) indicated that the “average” error achieved was 29%, a figure that falls within the acceptable error margins for this type of analysis.

The pre-mining in situ stress field can be estimated using the following equations:

- **Vertical Stress:**

$$\text{Sigma V} = 0.026 h$$
 (h depth below surface in meters)
- **Horizontal Stress EW:**

$$\text{Sigma EW} = 0.35 \text{ Sigma V} + 6.7$$
- **Horizontal Stress NS:**

$$\text{Sigma NS} = 0.36 \text{ Sigma V}$$

The identified error (29%) should be taken into account when utilizing the predictive model in future geotechnical analyses and design exercises.

4.3 Stress Measurements

A stress measurement campaign was implemented, utilizing the Hollow Inclusion (HI) cell measurement technique at the undercut level of the Underground mine. The aim of this campaign is to obtain values that will aid in validating the numerical models of the stress field.

The campaign includes stress measurements that are unaffected by the stress induced by mining, establishing a series of control points that led to

the corroboration of the values estimated in the calibrated numerical models. An example of this will be depicted in Figure N°4 below. (Please note that as a text-based AI, I'm unable to process or display images.

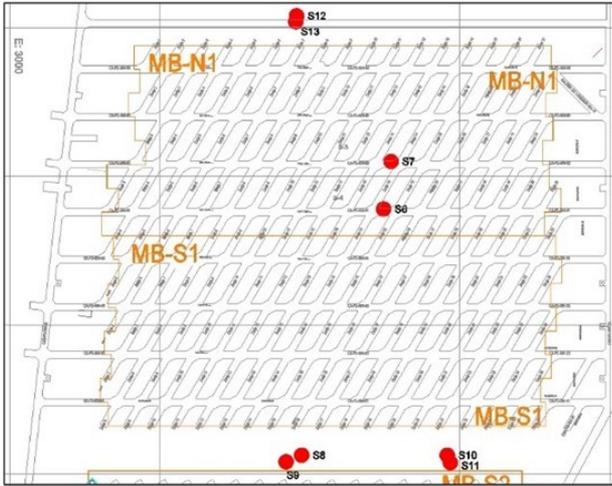


Figure 4 Stress Measurement Campaign MB N1/S1 Jan-Nov 2019 Chuquicamata Underground.

The outcomes of the conducted stress measurements are presented in Table N°1 below.

4.4 Stress Measurements versus Numerical Model with Flac 3D (Itasca 2015)

The results of the stress measurements were compared with the stress model that was previously calibrated in 2014 by Itasca. This comparison was conducted to evaluate the relative error between the numerical model and the measurements. The results of this analysis are presented below in Table 1.

Table 1 Comparison Stress Measurement versus Numerical Model

Site	Located	Sx	Sy	Sz	Sx	Sy	Sz	Error
S11	South	20.44	18.86	22.80	21.85	24.15	14.70	31%
S12	North	20.18	19.13	15.18	22.15	22.36	11.61	16%
S13	North	15.21	22.92	12.00	22.17	22.40	11.78	33%

The average error of the measurement campaign, in relation to the estimates made in the mine scale model (Itasca 2014), is 36%. From this, it can be inferred that the numerical model tends to overestimate the acting stress field compared to the ground measurement values.

5 CAUSAL ANALYSIS

The causal analysis of the main aspects that were part of the area incorporation of the macro block N1/S1 is described below.

5.1 Extraction Mesh Evaluation

A design review and stability analysis of the extraction meshes of Macro Blocks N1-S1 were conducted, in addition to outlining the main changes to the mining design. These changes include.

- Increased dimensions in the Production galleries, both in the production drifts and draw bells, and an increase in the undercut height.
- Elimination of the Ore pass on Drifts of the production level.
- Application of intensive Pre-conditioning (PA), using Hydraulic Fracturing (FH) and Confined Blasting (DDE) simultaneously.
- Increase in undercut height from H=10m in detailed engineering to an undercut height of H=20m in the reformulation study.

The main design parameters of the MB N1/S1 for the final engineering stages are described in Table N°2 below.

Table 2 Extraction Mesh Design Macro blocks N1/S1 Chuquicamata Underground

Desing Parameters	Detail Engineering	Reformulation Engineering
Extraction Mesh	16x16	16x16
Undercut height	10 m	20 m
Drift Distance	32 m	32 m
Draw Bell Distance	16 m	16 m
Drift Section	4,8 x 4,25	5,0 x 4,5
DrawBell Section	4,8 x 4,25	5,0 x 4,5
Crown Pillar	18 m	18 m
Mesh Type	Teniente	Teniente
Ore Pass	Yes	No

The analysis revealed that the restructured engineering designs led to a 9.6% decrease in the pillar area.

Table 3 Area and Perimeter Design Macro blocks N1/S1 Chuquicamata Underground

Design Parameters	Detail Engineering	Reformulation Engineering
Pilar Area(m2)	286,8	259,3
Pilar Area with Ore Pass	244,2	No
Pilar Perimeter(m)	78,0	79,73

5.2 Extraction Mesh Stability

The stability analysis of the extraction meshes yielded safety factors (FS) for the pre-mining, undercut, and extraction stages. This was applicable for both the detailed engineering stage with an undercut height of 10m and the reformulation stage with an undercut height of 20m. The findings are as follows.

- Zones with $FS \leq 1.0$ are located on the contour of the pillar, while the core primarily contains zones with $FS \geq 1.5$.
- As the incorporation progresses, the zones with $FS \leq 1.0$ increase, while the zones with $1.0 < FS \leq 1.5$ increase in the core of the pillar.
- $FS \leq 1.0$ in the contour of the pillar are considered common, reflecting the lack of confinement of the most superficial areas of the galleries, which increase with the advance and passage of the sinking front over the pillars.

A volumetric estimate of the stability condition of the pillars led to the following conclusions:

- Volumes with a Safety Factor ≤ 1.0 are lower for the mining design of the Production Level for Detailed Engineering compared to the Reformulation model.
- This is observed in all mining stages. When a comparison is made for the Abutment stress zone, it is evident that for the Detail Engineering mesh, the volume in the $FS < 1$ range is only 9%, while for the reformulation study it is approximately 21%.

- This difference increases when moving to the extraction stage. In the case of Detail Engineering, the volume of a pillar that is found with a $FS \leq 1$ is approximately 16%, however, for reformulation engineering the increase reaches up to 33%.

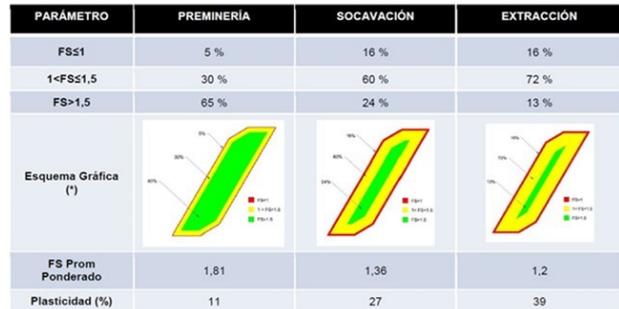


Figure 5 Safety Factor Detail Engineering with Undercut=20m.



Figure 6 Safety Factor Reformulation Engineering with Undercut=20m.

5.3 Overbreak Evaluation

This section outlines the analysis of the overbreak of the streets and pillars at the production level of the macroblock N1/S1. The analysis was conducted using scans from the I-Site equipment throughout the productive level work.

In Figure 11, the scanned work is depicted in green, and two analysis zones are defined. The first zone (indicated by a black dotted line) corresponds to the pillars that have a high percentage of their perimeter scanned. Conversely, the second area (marked by a red dotted line) corresponds to the pillars situated between two entirely scanned drifts. Even though it represents around 50% of its scanned perimeter, the aim is to observe the potential variation of overbreak from East to West due to the fluctuation in the quality of the rock mass.

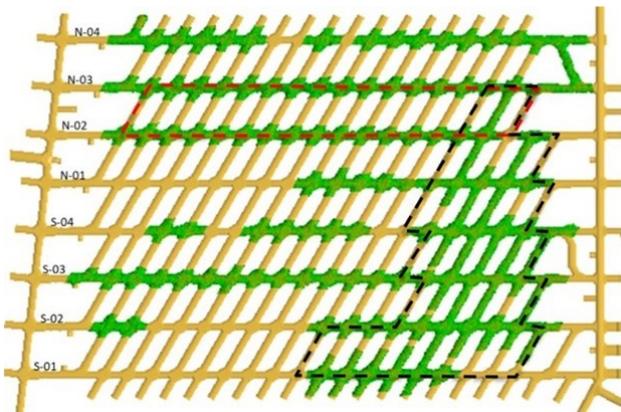


Figure 7 Scanned galleries and analysis areas Production Level MB N1/S1, Chuquicamata Underground.

In both analyses, horizontal cuts were made at 1 and 2 m from the floor, thus calculating the overbreak in relation to the design contour.

Initially, 30 pillars from the cuts made at levels 1824 and 1825 were analyzed. The overbreak was determined by comparing these with the design contour. The calculation of overbreak was focused solely on the scanned perimeter, which on average represents 79.3% of the total perimete.

Figure 8 illustrates the frequency of overbreak magnitudes along the contour of the pillars. For the cut made at level 1824, 60% of the pillars exhibit average over-excavations between 50 and 60 cm per wall. For the cut made at level 1825, 80% of the pillars have an average overbreak between 40 and 55 cm per wall. On a global scale, the recorded average overbreak corresponds to 46.8 cm for each wall of the pillar.

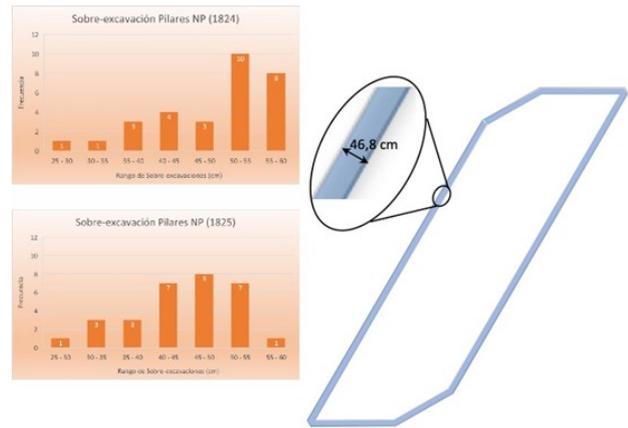


Figure 8 Analysis Results 1 Overbreak, Macro block N1/S1, Chuquicamata Underground.

When considering the area, the reduction ranges from 268.1 m² (theoretical pillar) to an average of 230.6 m². This equates to a 14% decrease in the pillar area. This is further detailed in Table 4 below.

Table 4 Pillar Overbreak Area 1, Macro blocks N1/S1 Chuquicamata Underground

Pillar Area	1824	1825
Average	229,1	232,1
Maximum	247,8	247,3
Minimum	220,8	221,3

The second analysis involved the assessment of 16 pillars beginning at levels 1824 and 1825. The overbreak for these pillars was analyzed by comparing it with the design contour.

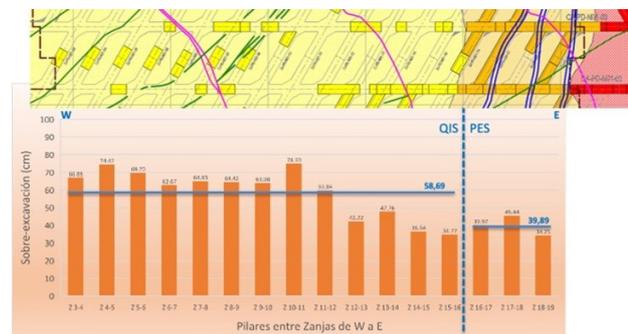


Figure 9 Analysis Results 2 overbreak, Macro block N1/S1, Chuquicamata Underground.

The prior analysis demonstrated that in terms of area, the range of obtained values is depicted. It revealed a decrease from 268.1 m² (theoretical

pillar) to an average value of 223.9 m², signifying a 17% reduction in area. This is illustrated in Table 5 below.

Table 5 Pillar Overbreak Area 2, Macro blocks N1/S1, Chuquicamata Underground

Pilar Area	1824	1825
Average	223	224,8
Maximum	239,8	242,0
Minimum	206,0	207,9

Alternatively, the over-excavation analysis of the drifts at the production level took into account 378 measurements of the percentage of pillar overbreak. The subsequent figure illustrates the percentage of drift overbreak.

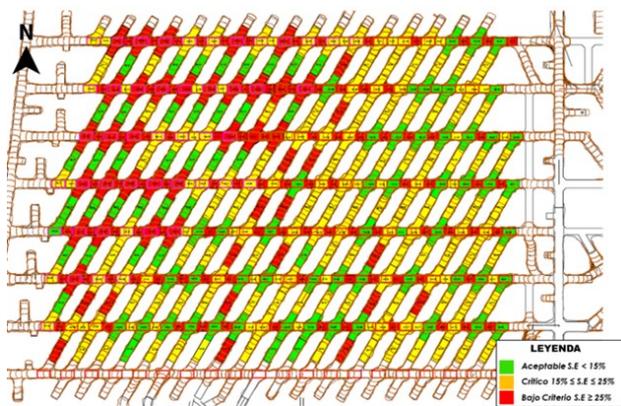


Figure 10 Plan View Pillar Over-Excavation, Macro block N1/S1, Chuquicamata Underground.

The analysis reveals that the majority of the area falls within the [20 - 25%] over-excavation interval, aligning with the critical criterion (indicated in yellow). Broadly speaking, 79% of the analyzed area fails to meet the over-excavation criterion (falling under the critical and below acceptability criteria; marked in yellow and red). Only 21% of the area adheres to the over-excavation standard, meeting the acceptable criterion (highlighted in green).

The over-excavation percentage analysis in the pillars indicated that they had an average percentage of 22%.

5.4 Support Design

Based on the productive layout and the equipment used, six distinct sections were

delineated between the Sinking Level and Production Level. At the Production Level, there are four different types of sections, as detailed in the subsequent table.

Table 6 Tunnel Design Macro blocks N1/S1 Chuquicamata Underground

Level	Galery	Section (m)	Excavated Section (m)
Undercut	Drift	4.0 x 4.0	4.0 x 4.0
	Cross Drift	5.5 x 5.0	5.7 x 5.35
Production	Drift	4.8 x 4.25	5,0 x 4,6
	Draw Bell	5.0 x 4.6	

The Fortification and Support design for the Production and Undercut levels were determined based on the rock mass classification (UCS and GSI). For instance, the following figure illustrates a typical design suitable for production streets situated in a rock mass of regular to good geotechnical quality.

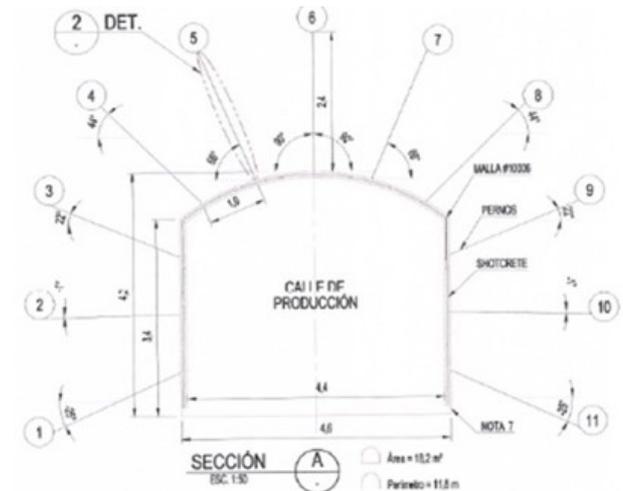


Figure 11 Section View Example Support Design, Macro block N1/S1, Chuquicamata Underground.

In the context of Detailed Engineering, it was decided to alter the sections, reducing them to just three types. For further clarification, refer to the upcoming table.

Table 7 Tunnels Section, Detail Engineering, Macro blocks N1/S1 Chuquicamata Underground

Level	Galery	Section (m)	Excavated Section (m)
Undercut	Drift	4.0 x 4.0	4.0 x 4.0
	Cross Drift	5.5 x 5.0	5.7 x 5.35
Production	Drift	4.8 x 4.25	5,0 x 4,6
	Draw Bell	5.0 x 4.6	

Later, during the reformulation stage, the sections were modified, with their dimensions at the production level being increased. The subsequent table provides a comparison between the two stages.

The primary modification involves the section of production streets, which was expanded to a section of 5.0 x 4.50 m. Consequently, the excavated section increased to 5.2 x 4.85 m, resulting in a single section for the production level, as depicted in the next figure.

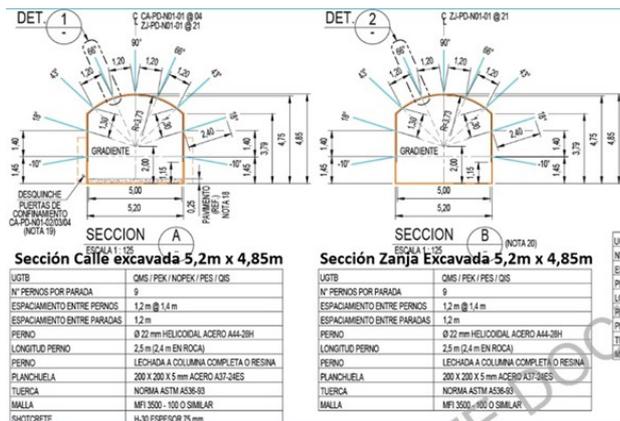


Figure 12 Final Support Design, Macro block N1/S1 Chuquicamata Underground.

Lastly, as part of the fortification design reviews conducted by specialists from the El Teniente Division, it was concluded that it would be beneficial to reinforce and confine the pillar with walls 1.8 m high and 10 cm thick. This evolved into 15 cm excavated reinforced concrete, complete with wire brackets and bolts.

5.5 Analysis Abutment Stress

The conducted analysis takes into account the progression of the cave front and the incorporation of the area, in relation to the

mining activity performed. This specifically refers to the rate of advancement and the exposure time in the abutment stress zone, areas where the fortification and the rock mass have experienced significant deterioration.

Considering the actual advancement sequence of the N1/S1 macroblock, the following figures display the analyses performed. Each image highlights (with a red border) the collapsed areas of the N1/S1 macroblock, from which it was possible to determine the following:

- Length from the Cave Front on the pillars of the Production Level.
- Abutment Stress Time on the pillars of the Production Level.
- Time from the opening of the basin adjacent to the pillar until the Cave Front advance.

The subsequent figure represents a diagram of the length from the cave front measured on the half pillar of rock. This is represented by the sum in meters of the cave front stops burned on the pillar of the production level.

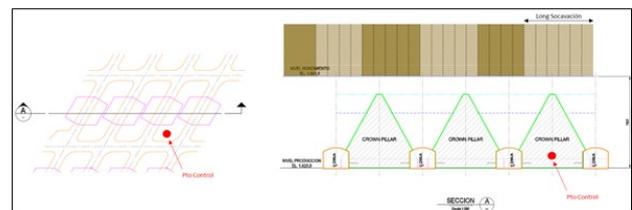


Figure 13 Plan View Pillar Over-Excavation, Macro block N1/S1, Chuquicamata Underground.

The results concerning the distance of the cave front on each half pillar, shown in the central area of the N1/S1 macroblock, indicate that blasting exceeded 20 m (Red Color), i.e., blasting of 9 or more stops was carried out per time. A similar situation was observed on the collapse of 3 North East Street, and in part of the collapse of 3 North West Street, but the latter presented lengths close to 16 m (Green Color). It's noteworthy that areas with undercut lengths of 20 m were evident in the South-East zone of the macroblock, which did not register significant damage (collapses) at the production level.

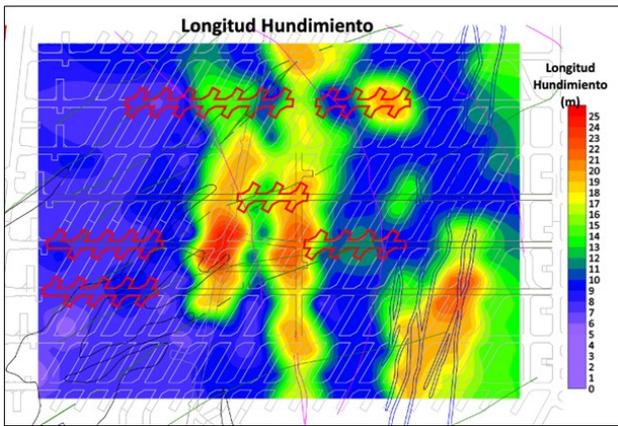


Figure 14 Plan View Length Over Pillars, Macro block N1/S1.

The following figure represents the abutment stress times for each drift of the N1/S1 macro block. Several areas stand out with abutment times over 100 days, which coincide with areas with a collapse in the level of production, such as Calle 3 Sur Oeste, 3 Norte Oeste and Este, and on the west side of Calle 1 Norte. This exceeds the progress times defined as geomechanical guidelines, which correspond to approximately 60 days. It should be noted that on Calle 1 Sur-Este of the macroblock, Calle 1 Sur, there is an area where the abutment time exceeded 100 days, this area not registering damage at the production level.

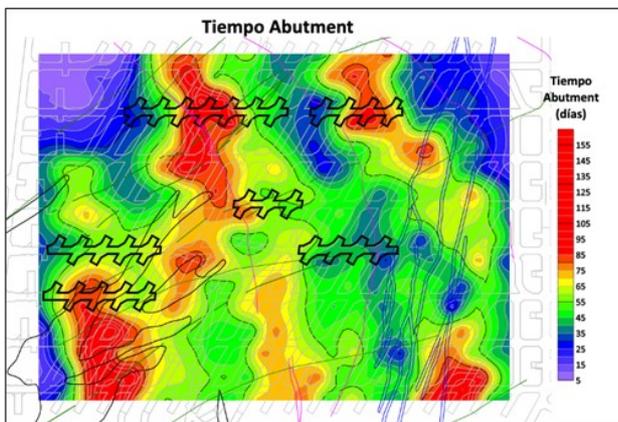


Figure 15 Abutment Stress Period Over Pillars, Macro block N1/S1.

Figure N°16 shows the elapsed time from the opening of the draw bell to each pillar until the incorporated area exceeds it, which would represent the start time of the effect on the rock mass of the pillar in the abutment stress zone. The above shows areas with high times which reach 150 days in several areas, and also

coincide with areas with the presence of collapses in the level of production.

5.6 Analysis Drilling and Blasting Design

The assessment of the drilling and blasting designs for drawbell and caving took into account geometric compliance, connectivity, and damage. Here are the key findings from this review:

- The design's primary vulnerability lies in the theoretical size of the largest apex, which accounts for 18% of the total surface area defined by the center of four trenches with a width of 5.5m, compared to 10% with a width of 3.3m in El Teniente Esmeralda. This width is highly susceptible to deviations in the execution of negative shots, whether due to overbreak of the UCL drifts, drilling or explosive loading deviations, or detonation failures. If one of the shots defining the crown pillar cannot be loaded or has a detonation issue, the width of the largest apex increases from 5.5 m to 6.9 m. This risk is significant, as due to overbreak, 7% of the collars are less than 10 cm from the floor. This vulnerability is primarily due to the diagram of negative shots initiated from the UCL drifts.

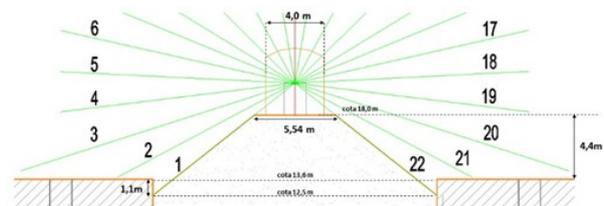


Figure 16 Auscultation Design Since Production Level Macro blocks Chuquicamata Underground.

- In contrast, the triangular platforms at the discharge level only represent 10% of the total surface and are not, in principle, a critical element of the theoretical design. However, it's unlikely that these platforms will be constructed as planned, due to the burden that negative rolls should move onto them (up to 3 burdens). The final geometry of these sectors is expected to be highly irregular, with potential formation of support points or arches, and non-compliance with the flow angle, which is already low by

design (38° vs 45° to 50° in El Teniente). This condition could worsen in case of deviation in trench construction and the two most closed vertices.

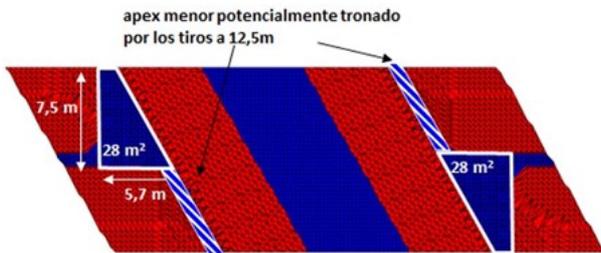


Figure 17 Auscultation Design Since Production Level Macro blocks.

- In El Teniente Division, these platforms are blasting with the negative shots of the Undercut Level.
- The construction of the drawbell in a single phase should be achievable, provided that adequate fragmentation is obtained and a sequence is followed that allows the blasted material to be moved towards the production drifts, without freezing in the most closed sectors of the drawbell. A comparison with tests conducted in the El Teniente Division reveals that for the same load factor, the granulometry (P80) is double in Chuquicamata. It's unclear if this is due to different geomechanical conditions or issues with explosive performance. Additionally, the sequencing strategies differ, with faster blasting in DCH and different iso-timelines.
- To mitigate the risk of creating a narrow drawbell, the position of the detonator in the explosive column must be reviewed to ensure that sufficient energy is available in the roof sector, particularly in the tightest corners of the drawbell. The use of vertical stops tends to increase the risk of generating a concave roof.
- To adhere to crown pillar geometry or avoid a narrow drawbell, it's crucial to review drilling practices and deviations.

5.7 Preconditioning

The following section outlines the implementation of Preconditioning, with a primary focus on Hydraulic Fracturing. This

focus is due to its traceability in terms of well numbers, fracture quantity and analysis, pumping pressures (both rupture and propagation), flow rates, and so forth.

The program for well drilling and Hydraulic Fracturing, which includes hydrofractures at intervals of 1 and 1.5 m, results in a hydrofracture density ranging from 0.78 to 0.81 FH per linear meter of drilling.



Figure 18 Preconditioning Design Since Production Level Macro blocks Chuquicamata Underground.

Table 8 Desing Parameters DDE, Macro blocks N1/S1 MCHS

Drill Hole	Lenght (m)	FH
FHN42	150	122
FHS6A	285	212
FH1A	180	142
FH1B	180	142
FHS1A	170	132
FHS1B	170	132
FHN2A	195	152
FHN2B	195	152
FHS2A	150	122
FHS2B	150	122
Total	1825	1430

Considering fractures with registration (pressure/flow versus time curves) and an injection volume exceeding 3 m³, the fracture count stands at 417. This figure represents 74% of the planned fractures and merely 31% of the total potential fractures.

In contrast, preconditioning via confined blasting is designed to delineate disturbed and interaction zones between wells. The goal is to potentially lower the rock mass's resistance, thereby forming an “explosively preconditioned” zone.

For the DDE applied from the production and undercut levels before the undercut process,

ascending drilling techniques were employed. These techniques involved variable lengths ranging from 120 to 150 meters and drilling diameters between 146 to 165 mm.

6 RESULTS & FINAL COMMENTS

The study's findings and observations will be presented as follows.

6.1 Pillars Design

- The transition from basic engineering (4.6 x 4.25) to the reformulation stage (5.2 x 4.85) led to an increase in the sections' width and height by 0.6 m and 0.65 m, respectively. This resulted in a reduction of the design rock pillar by 0.6 m in length and 0.8 m in width (López, 2021).
- The expansion of the section of streets and ditches decreased the effective pillar area, leading to an increase in the pillar area in a state of limit stability from 9% in the abutment stress zone in detailed engineering to 21% in the reformulation stage.
- The modifications made in the rock pillars' design from the Detailed Engineering to the Reformulation stage resulted in them being in a state of limit stability (Barindelli, 2021).

6.2 Overbreak Drifts Production Level

- The pillars' stability condition has been impacted by overbreaks, which are primarily related to Construction Quality, Structural Domains, and Rock Mass Quality, with no evidence of damage due to over-stress (Constanzo, 2021).
- The average over-excavation of streets at the MB N1/S1 production level corresponds to 22%.
- The area reduction of the pillars at the MB N1/S1 production level averages 16%. Adding the effect of the parallelism mentioned in point ii, a disassembly of the rock pillars is anticipated under this condition (Lopez et al. 2021).
- 77% of the pillars of the N1/S1 macroblock have an area reduction of 15% or more.

6.3 Support Design

- The disassembly mechanism in the pillars begins with cracking on the concrete walls until they topple. A support solution was evaluated that allows for the absorption of the greatest deformations (up to bending) and considers a less rigid fortification or one with a higher absorption capacity (Barindelli, G. 2021).
- The design anchor length of the installed confinement walls was insufficient for the degree of deformation that the pillars exhibited during the mining exploitation process.
- The design fortification was not suitable for the expected plasticity levels, especially when comparing the fortification design with the mechanism observed on the ground (disassembly of the pillars) and what is indicated in the numerical models (Barindelli, G. 2021).

6.4 Abutment Stress & Damage Support

- The rock mass of pillars and rafts, particularly for the QIS unit (70% area), experienced accelerated deterioration of the fortification and rock mass due to excessive exposure time to abutment stress (100-150 days) (Galvez, F. 2021).
- To minimize the exposure time to abutment stress, it's essential to continuously advance the cave front and incorporate drawbells in extraction, maintaining a line of open drawbell ahead of the cave front.
- The fortification installed for the N1/S1 macroblock showed rapid deterioration, declining from 85% in good condition in early February 2020 to 20% in November 2020 (Lopez, S. 2021).
- The process of connecting to the Rajo significantly impacted the deterioration of the rock pillars fortification between February and April 2020, dropping from 63% in good condition to 25% (Constanzo, H. 2021).

6.5 Drilling and Blasting Evaluation

- The theoretical caving drilling design results in the Greater Apex having a width of 5.5 m.

Excessive apexes contribute to the generation of loads on the Crown Pillar.

- If the shots that define the Crown Pillar (negative shots 1 or 28) cannot be loaded or encounter detonation issues, the width of the Apex Mayor could increase from 5.5 m to 6.9 m or more (Lopez, S. 2021).
- The D&B design, situated between the undercut and the drawbell roof, creates triangular platforms (16 m²) that allow material accumulation, forming "rock piles" which could "transmit loads" through the Crown Pillar towards the production pillars.

6.6 Preconditioning

- The execution of Hydraulic Fracturing didn't include any morphology tests for the N1/S1 macro block, which would have enabled the validation of design criteria (Farias, E. 2021).
- Out of the 417 planned fractures, only 51 fractures were executed (12%). This is deemed a low percentage of FH implementation.
- The application of DDE resulted in damage to the drawbell galleries extending approximately 100 meters in front of the cave front.
- No noticeable contribution was made to the size reduction of the applied preconditioning, whether it was FH+DDE or DDE, in the rock mass (QIS) of the N1/S1 macroblock (Constanzo, H. 2021).

6.7 Final Comments

Upon considering the aforementioned information and the conducted causal analysis, the following observations can be made:

- The primary cause is linked to a pillar design that is on the brink of stability, in a rock mass of average to poor geotechnical quality, and with a high overbreak, a 22% in the production level galleries. This led to 50% of the pillars of the macroblock being in a failure condition ($FS < 1$).
- This situation was exacerbated by an inadequate support design, rapid deterioration of the fortification, the impact

of abutment stress, and a vulnerable drill and blast design.

- Additionally, certain operational aspects that had an impact included flat extraction geometries, the loss of radial shots at the undercut level, and the irregular geometry of the drawbell.
- In line with the above, the study's hypothesis was validated, which identifies the main factors contributing to the occurrence of instabilities: a pillar design that was at the limit of acceptability, and that was also affected by a high over-excavation of streets and ditches. This meant that when the mine exploded, 50% of the pillars were in a failure condition.

ACKNOWLEDGEMENT

This study was carried out for the professionals of both the Planning Underground Mining Superintendence and Geomechanical Superintendence, which are integral parts of the Mining Resource & Development Management.

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