Winter Operations in the Large Scale Andina mine Division in the Chilean Andes: Challenges and Strategies
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ABSTRACT: Operating a large-scale state owned mining division in the Chilean Andes during winter presents unique challenges due to high mountain roads and numerous avalanche paths. This proceeding focuses on the winter operations of a mining division with more than 7000 employees, where a dedicated team handles avalanche forecasting and control. The region experiences central Andes climate with copious snowfalls in short periods of time, followed by sunny stable weather, which adds to the complexity of operations.

One of the biggest challenges faced by the mining division is to manage the worker shifts in alignment with the avalanche danger forecasting. A poor forecast can lead to a complete working shift of more than a thousand workers being blocked inside the mine, while the fresh working shift outside is unable to enter, creating significant economic losses and tensions with workers unions. To address this challenge, the winter team has developed a pre-warning alert system that splits the working shifts in advance and allows for operational flexibility to prevent shutdowns.

The mining division operates in an area with over 200 main avalanche paths along 35 km valley, making it necessary for the winter operations team to handle avalanche forecasting and control. The dedicated team uses the latest technology, including remote sensing, field observations, and expert analysis, to forecast avalanches and determine the appropriate control measures. These measures include RACS systems, pneumatic cannon, and hand charges to mitigate the risks of avalanches.

In conclusion, winter operations in a big scale mining division in the Chilean Andes require specialized expertise and strategies to handle the unique challenges posed by the region's mountain weather and avalanche-prone terrain. The winter operations team's pre-warning alert system and effective avalanche control measures play crucial roles in ensuring the safety of workers and preventing economic losses to the country.

Keywords: snow avalanche, avalanche control, avalanche protection, risk management, mining.

1. INTRODUCTION

The Chilean Andes, characterized by their formidable topography and distinctive climatic conditions, serve as the backdrop for an essential industrial endeavor – the winter operations of a copper mine located on the Chilean side of the central Andes. This proceeding examines the dynamics of this mining operation and the winter operation, exploring its economic significance, historical foundations, geographic context, and the scientific challenges posed by its alpine environment.

With a workforce comprising both direct and indirect employees, totaling 7,000 individuals, the mine plays a pivotal role in the regional economy. The mine's annual output of 183,000 tons of refined copper and 1,660 tons of molybdenum contributes substantively to the state owned Codelco group. This economic impact resonates locally, shaping the economic landscape of the Los Andes region and beyond.

Nestled within the Rio Blanco Valley see fig. 1, the mining operations extend across a considerable span of 35 kilometers, spanning elevations ranging from 1,600 to 4,200 meters above sea level. Notably, the historical contributions of Montgomery Atwater, the inaugural snow supervisor during the 1960s see fig. 2, underpin the mine's operational strategies. As the architect of the initial snow operations manual, Atwater (1965), Atwater's legacy informs contemporary practices, guiding the mine's winter operations within the context of evolving scientific understanding.

The Rio Blanco Valley, where the mine operates, is marked by a notable natural feature – approximately 200 registered avalanche paths. Negotiating this complex terrain underscores the inherent chal-

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Figure 1: Map of the region where the Codelco Andina mine division is located (red cross).

lenges of winter operations, necessitating the integration of geological, meteorological, and engineering expertise to ensure operational continuity and safety.

Within the broader context of the Chilean central Andes, the region experiences a climatic interplay characterized by a convergence of maritime and continental influences. The ensuing winter conditions are typified by extreme cold and substantial snowfall. These climatic conditions, combined with the challenging topography, underpin the necessity for snow science, advance technology and avalanche management protocols.

2. The Codelco Andina Winter Operations in numbers

2.1. Snow Precipitation and Historical Context

The Andina mine's winter operations are intimately shaped by the prevailing snow conditions in the Chilean Andes. Over the span of 32 years, from 1991 to 2023, snow precipitation has been meticulously measured on an hourly basis (storm profile) at the meteorology building, Lagunitas 2765 m.a.s.l. Accumulating to a substantial 833 centimeters during this period, this data provides crucial insights into the region's snowfall patterns and guides the mine's operational decisions.

Figure 2: Photo from M. Atwater in the Andina mine at the time he wrote the first 'Operations Manual – Snow and Avalanches' for the mining operation in 1965. (Photo P. Kyburz.)

2.2. Safety Challenges and Avalanche Protection

Winter operations at the Andina mine are not without their challenges. In the course of four decades, the mine has experienced six fatal accidents directly attributed to avalanches, underscoring the urgency of effective safety measures, León (2003). Additionally, 25 accidents have led to damage to key mining infrastructure, resulting in some cases in total losses.

Addressing these risks has prompted substantial investments, with the mine channeling a total of 240 million dollars into avalanche protection endeavors. This comprehensive strategy encompasses both active and passive methods of mitigation. Notably, the pinnacle of these efforts is embodied by the colossal catching wall in the NODO 3500 sector, see fig. 3. Stretching an impressive 270 meters in length and towering at 25 meters in height and 25 meters width. At an elevation of 3,532 meters above sea level, it claims the distinction of being the largest avalanche catching dam ever constructed at such altitudes, Florian Rudolf-Miklau (5 December 2014).

2.3. Avalanche Control and Monitoring Systems

Integral to the mine's winter operations is the set of remote avalanche control systems (RACS) deployed strategically across the operations area. Comprising 36 Gaz ex exploders, 52 Wyssen towers, 4 O'bellx, and 2 Avalancheur Lacroix systems, these technologies form the backbone of the mine's proactive avalanche management strategy, see table 2.3. Operated by an internal Codelco winter team (2 senior avalanche experts plus 2 meteorologist and the unit director and meteorology director), supported by a subcontracted team for the winter operation made up of ten professionals, this team enable daily avalanche danger assessments and the formulation of essential operational insights.

Figure 3: Overview from the strategic operational NODO 3500 sector where the main crusher of the open pit is located. On the left side the catching dam 25 meter height and width and 270 meter long protecting the East side of the area.

In concert with these advanced systems, the mine boasts a network of 11 remote automatic meteorological stations and avalanche detection systems. This ensemble includes 13 geophones and 8 Doppler radars, furnishing the winter team with precise meteorological and avalanche-related data critical for decision-making.

RACS (installation period)
41 Wyssen towers (2018-2023)
32 Gaz Ex (1996-2018)
4 O'bellx (2018)
2 Avalancheur Lacroix (2010)
10 Wyssen towers project (2024)
1 C.A.T.E.X (2007-2020)
2 Howitzer 75mm (1968-1995)

2.4. *Meteorological Precision and Timely Alerts*

Central to the mine's safety protocol is the issuance of pre-warning alerts ahead of impending snowstorms. Disseminated to 4,000 stakeholders, including local authorities and three worker unions, these alerts epitomize the mine's commitment to proactive hazard mitigation.

The Codelco operations are fortified by a rigorous alerts system that plays a pivotal role in maintaining operational integrity during challenging winter conditions. This system communicates various levels of actions and implications, all of which are meticulously incorporated into the Winter Operations Regulation and demand acknowledgment from every unit within the mine, see fig. 4.

- Alert 1: This alert signals the imminent approach of a snowstorm to the industrial area. Non-essential workers are required to vacate the industrial area during the next working shift, and those currently outside the mine must refrain from entering in the subsequent working shift.
- Alert 2: Activated when a snowstorm is in progress within the area, Alert 2 prompts road closures. All surface movement necessitates authorization from the Winter Operations Team, restricted to areas designated by the Winter Regulation. The announcement of avalanche control measures is expected, and personnel and equipment tasked with snow removal are required to await instructions from the Winter Operations Team.
- Alert 3: This alert designates a situation of high avalanche danger in the area. In response, all surface movement is strictly prohibited, all mining activities on the surface must stop, including stopping the crushing feed at NODO 3500.
- Alert 4: Following the snowstorm's passage, Alert 4 is issued to communicate the post-storm scenario. Announcements pertaining to road and area clearances are disseminated through established communication channels by the Winter Operations Team.

Figure 4: Internal Codelco Andina Winter regulation flow chart

This alerts system serves as a strategic cornerstone, effectively orchestrating actions and responses across the entire operational landscape. Each alert level not only conveys critical risk information but also delineates specific actions and responsibilities, ensuring a well-coordinated approach to address the dynamic challenges posed by winter conditions.

A dedicated snow removal team forms an integral facet of the mine's winter operations. With a fleet of 12 snow cats, alongside bulldozers till the D-11 variant, front loaders as big as the Letorneau I-1800, and CAT 24 m motor graders hailing from the mine operations, this team ensures operational continuity by efficiently managing snow accumulation. Furthermore the mine holds a helicopter service contract where operations can request helicopter service for field work, snow observations or in extreme cases avalanche control through Helibombing.

3. Design of the protection measures and operational criteria for the NODO 3500

It is a project that considers replacing the current primary crushing mineral system with a new primary crushing station located on a platform called NODO 3500, to ensure processing capacity to compensate for the closure of the underground mine and reach full operation pit with a nominal treatment capacity of 94.5 kt/d.

refThis platform was in a red zone T = 100 and, large intensity ($p > 30$ kPa) at the foot of a series of avalanches that come from the upper basin of Cerro Negro located at more than 4000 meters above sea level, it is Potential avalanche start zone is an area of more than 60,000m2 that for a return period is estimated to generate avalanches of a volume greater than 500,000m3. The question is why build the heart of the mine here? Simple answer, it is the best balance point for the transit of ore and ballast to the dump, see fig. 3.

In 2008, the platform began to be built that contemplated a design of continuous operation 365 days a year without human intervention, only based on passive defenses for a return period of 100 years. In 2016, as a result of economic variations in the price of copper, it was decided optimize the design by reducing its investment cost but changing its operation criteria, where a discontinuous operation is assumed leaving at least 5 days per year of stoppage, incorporating human management with redundant RACS, remote avalanche detection systems and maintaining clear of snow the passive defense structures, see fig. 7.

The large defenses built made it possible to go from a red zone ($p > 30$ kPa) in 2009 to a yellow zone T = 100y and, small intensity ($1 < p < 3$ kPa) or residual risk in 2021 for an area of 16.5 hectares. Going from an area that it remained closed for more than 400 hours a year, sometimes at 0 hours a year from 2021 onwards, managing to operate with the power of the crusher with high-tonnage trucks during storms with precipitation rates over 15cm/h and winds of 130km/h.

This is achieved thanks to a comprehensive operation that puts people at its core. This approach encompasses engagement with unions, performance dialogues, early warnings, and a comprehensive management process extending beyond the technical aspects of avalanches. The strategy encompasses key facets like understanding disaster risk, avalanche mapping Christen et al. (2010), training, communication, and risk management through monitoring, analysis, and predictive threat assessment. Timely Early Warning Bulletins are disseminated, and dialogue-based performance (Lean Management) planning is undertaken, spanning aspects such as labor, supplies, logistics, and, most crucially, the integration of lessons learned from each storm event, see fig. 4.

4. Designing Criteria for Installing Remote Avalanche Control Systems (RACS) in High Alpine Mine Operations Road

In the context of high alpine mine operations, the installation of Remote Avalanche Control Systems (RACS) is a critical endeavor aimed at ensuring the safety and efficiency of industrial roads in avalanche-prone regions. The strategy used in the Andina division for designing an effective RACS deployment is intricately woven with the careful consideration of a myriad of factors. These include historical avalanche data, avalanche hazard maps, snow-meteorological records, and the broader contributions of Gubler's work in the field, Gubler (1976), Gubler (2012). Within the context of the Codelco Andina mine, the decision-making process for RACS installation is underpinned by an array of valuable data-sets, which together provide essential insights into avalanche occurrences and snowpack behavior. This section outlines the key designing criteria and other crucial information to determine the optimal placement of RACS within the specified mine operation area.

4.1. Historical Avalanche and Meteorological Data

The historical record of avalanches along the industrial road sector, especially in the decades preceding the project, stands as a foundational dataset for RACS placement. The insights of the historical information on average frequencies and dimensions of avalanches from the 1970s, collectively enrich the understanding of the frequency and magnitude of past events. The mentioned records combined with the record of snow-meteorological data gathered from the ALPUG snow-meteorological station network over the past 10 years, yield a profound comprehension of snowpack behavior. This data provides critical inputs for assessing snowpack stability, accumulation rates, temperature fluctuations, and precipitation trends, Vera Valero et al. (2016).

All this information was summarized withing the avalanche hazard map prepared by the Swiss Federal Institute for Snow and Avalanche Research (SLF) during 2009-2011 Margreth, details flow height, velocity, intensity, slopes, and avalanche paths. This data assists in identifying high-risk zones and in selecting optimal locations for RACS

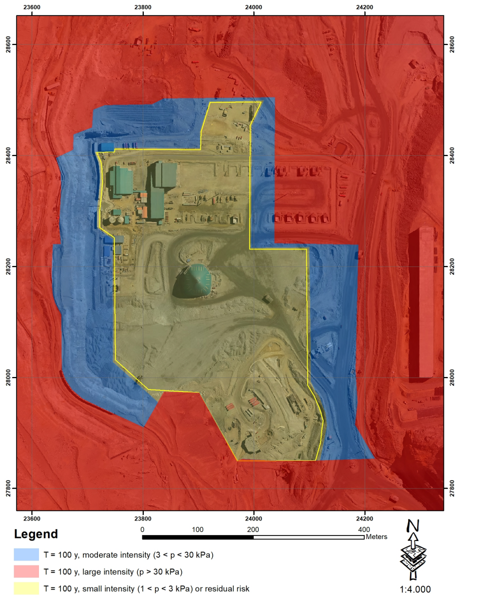

Figure 5: Avalanche Hazard map of NODO 3500 with protection measures

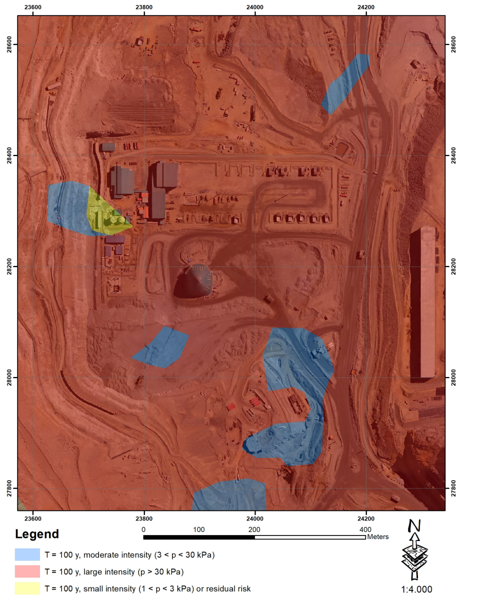

Figure 6: Avalanche Hazard map of NODO 3500 without protection measures

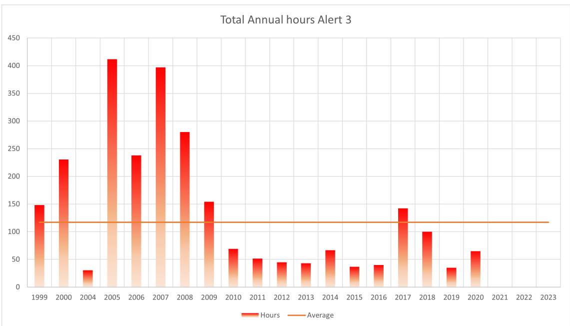

Figure 7: Amount of Hours of Alert 3 issued in the operations area of the mine. Alert 3 state all operations in surface are forbidden due to avalanche danger. Note the decrease after the construction of active and passive control methods.

deployment to counter potential avalanche threats, see fig.8.

4.2. Criteria used for the RACS installation

The following criteria outline the overarching principles that guide the selection of RACS positions for both the first and second phases of the project:

First Phase Criteria:

- Prioritizing High-Risk Paths:The initial focus of the first phase is on mitigating avalanches on paths that most frequently affect the industrial road, even in cases of low precipitation rates. These paths, causing road closures with as little as 20 cm cumulative snow and 1-2 cm/hr precipitation rates, take precedence.

- Comprehensive Sector Control: Beyond addressing high-risk paths, the first phase aims to partially mitigate risks in all sectors up to kilometer 21. While controlling all hazards in certain sectors isn't feasible in a single phase, focusing on critical areas within larger sectors is a priority. The experience gained from this phase will inform subsequent phases.

- Testing and Decision-Making: The control of main paths allows for partial risk mitigation and offers a significant opportunity to assess avalanche activity. This serves as a robust test of avalanche behavior, contributing to better decision-making for subsequent phases.

Final Position Determination: Once paths are chosen for control, RACS tower positions adhere to the following guidelines:

- Starting Area Consideration: Favoring upper areas of the paths, covering the widest possible area with inclinations between 32-45°, known to be conducive to avalanches.

- Wyssen Tower Range: The Wyssen Tower's 120 m estimated action radius from the detonation point is optimized to cover the maximum starting area with detonation.

- Construction Considerations: Optimum detonation points inform construction, considering factors like ease of access, suitable soil for foundations (preferably competent rock over loose soil or poor-quality rock), and crew safety and comfort.

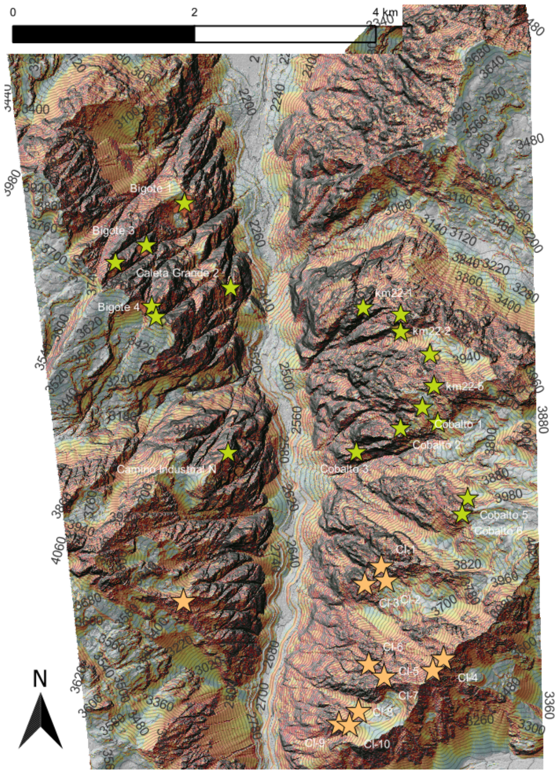

Figure 8: Approximate positions from the 27 Wyssen towers installed between the km-21 and the km-28 of the Codelco Andina Industrial road.

Second Phase Criteria:

The second phase focuses on mitigating residual avalanche risks after the execution of the first phase:

- Informed Decision-Making: Insights gained from the first phase guide the identification of areas not covered that still pose risks to operations.
- Completing Control: The aim is to complete control in areas not covered during the first phase but still demonstrating proven risks.
- Residual Evaluation: After each control executed in the first phase, an assessment of residual risk in each sector guides the second phase planning.
- Feasibility Study: A feasibility study establishes points for the second phase, aiming to cover all avalanche start areas affecting the industrial road based on available information and field visits. These points are confirmed post-execution of the first phase.

In essence, the criteria for RACS placement in the Codelco Andina project encapsulate a comprehensive approach. It integrates historical data, modeling insights, meteorological records, Gubler's recommendations, and the experience gained from successive phases to optimize RACS placement. This iterative process aims to effectively mitigate avalanche risks and enhance the safety and operational integrity of the industrial road.

The successful installation of the second phase avalanche towers in April 2023 marked a significant milestone in our operation, see fig.8. It is premature to fully quantify the precise benefits of the newly implemented system, we are already witnessing improvements in crucial aspects of our operations. Notably, the expediency with which we can mobilize snow removal teams stands out as an immediate advantage.

Moreover, the new systems empowers our forecasters to meticulously select the opportune moment for initiating avalanche releases. This deliberate decision-making process extends to both the timing and the size of the controlled avalanches. A critical factor at play is the sheer size of the valley and its avalanche paths, which has the potential to transform a spontaneous avalanche into dimensions that pose formidable challenges to the snow removal team. By controlled releases, we pursue to manage the dimensions of these events, thereby optimizing both safety and operational efficiency.

5. Climate change and possible impacts on the mine operations

The executive leadership of Codelco Corporation has initiated an internal investigation across all divisions to assess potential scenarios related to climate change that may impact mining operations. While this endeavor is an ongoing process, the Winter Operations team at Andina has taken proactive steps to compile and analyze the most recent meteorological occurrences that could potentially be attributed to climate change.

- One such notable event occurred between June 20th and 23rd in 2023, during which an unprecedented 332 mm of rain was recorded at the Saladillo camp. This event coincided with an isothermal reading of 0 degrees Celsius at an elevation of 3200 meters above sea level. The convergence of these factors resulted in flooding during the high winter season. This situation necessitated the evacuation of nearly 2000 individuals, prompting the rigorous testing of natural hazard maps designed for a 100-year return period, see fig. 9.

Even though it is a work in progress the Andina Winter Operations teams is already preparing contingency plans with the following focus points

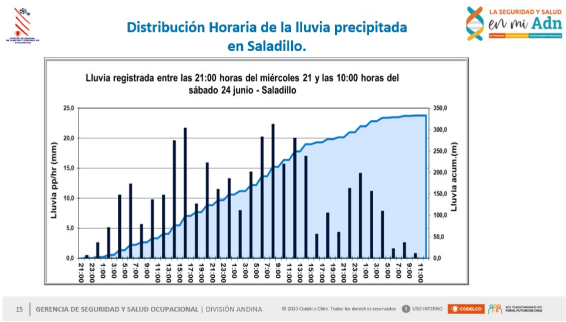

Figure 9: Graph showing liquid precipitation measured in the Saladillo camp at 1685 m.a.s.l. published internally by the Codelco Andina Meteorologic service after the rain event between the 21st and 24th of June, 2023, (in spanish). The left 'y' scale shows the hourly liquid precipitation and right 'y' scale shows the precipitation accumulated during the storm.

- Events of rain on winter snow cover causing a dramatic increase on wet snow avalanche danger.
- Warm fronts events where the high temperature lead to rain on high altitudes during several days leading to debris flows in high altitude valleys where this danger has not been observed yet.
- Extreme precipitation events where the precipitation rate has not been recorded within the mining operation areas.

In response to these emerging challenges, Andina is diligently crafting internal protocols to effectively manage and mitigate the impact of potential occurrences as outlined above. Through a robust preparedness approach, the aim is to ensure that the mine's operations are well-equipped to handle the complexities brought about by these evolving climate-related scenarios.

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