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Excavation and support of ventilation shafts with blind hole methodology in the Andes Norte project

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Abstract

After 118 years of operation at its emblematic El Teniente mine, Codelco seeks to extend the mine's useful life by more than 50 years with the exploitation of the deposit through the new mine level (Nuevo Nivel Mina in Spanish, or NNM) which includes the Andes Norte, Andesita, Diamante and Recursos Norte projects. The project adds 2,020 million tonnes of reserves with average grades of 0.86% copper and 0.022% molybdenum. This translates to more than 17 million tonnes of fine copper over the 50 years of operation (which commenced in 2018). The configuration of the project comprises exploitation through the panel caving method, with 100% of the area preconditioned with hydraulic fracturing and a typical level scheme of the El Teniente mine: caving, production, ventilation, transport and primary crushing.

This paper describes the support of ventilation shafts in an unfavourable rock area within the Andes Norte project. This adversity is intensified by the hydrofracturing required for development works due to the stress to which the rock mass of the project is subjected as a result of high stress and anisotropy. The objective of these vertical excavations, or ventilation shafts, is to facilitate the injection of clean air from outside the mine and the extraction of contaminated air from inside.

The construction process of these shafts begins with the drilling of a pilot hole that takes the same trajectory as the planned shaft. This is followed by the mechanised excavation using a blind hole machine. The ground support process includes the installation of lifting instruments and manual insertion of galvanised corrugated liner (referred to as a steel liner at this stage) which is then lowered down the shaft until it reaches the bottom. Next comes concreting of the annular space between the liner and the excavated rock of the shaft. This paper discusses the operation, lessons learned and how certain unique challenges were addressed during the construction phase. The goal is to initiate the ventilation system for the various levels of the project.

Keywords: *El Teniente, ventilation shaft, panel caving method*

1 Introduction

'The Andes Norte project, part of the Nuevo Nivel Mina (NNM) in the El Teniente Mine, which is estimated to begin production in October 2023, requires a ventilation system that injects clean air from the surface and extracts stale and contaminated air from the various levels of the mine, expelling it to the surface. As a result, this ventilation system designates the use of ventilation shafts as the means of connection between the ventilation level and the different levels that comprise the project. Due to the geomechanical conditions of the rock mass in the production sector and the project requirements, these shafts must be fortified to preserve their excavation and maintain them throughout operation.' (Rodriguez et al. 2023)

2 Geotechnical backgrounds of the Andes Norte footprint

The backgrounds that justify the requirement of ground support for the ventilation shafts located in the production sector of the North Andes footprint are presented.

2.1 Footprint geotechnical environments

Variations are observed in the geotechnical behaviour across different sectors of the Andes Norte footprint. A range of factors can explain this, including the main structural systems, the presence of lithological bodies, the strength and stiffness of the intact rock/rock mass, stress magnitudes and orientations, mining activity in upper levels and the rock column, among others. These factors condition our excavation processes and/or shaft reaming to varying degrees.

2.1.1 Lithology

The mining area of the Andes Norte project, as shown in Figure 1, is predominantly characterised by rock from the El Teniente mafic complex (CMET, when translated from Spanish to English). The central part of this area is formed by felsic bodies (dioritic porphyry), as well as hydrothermal breccias and igneous breccia.

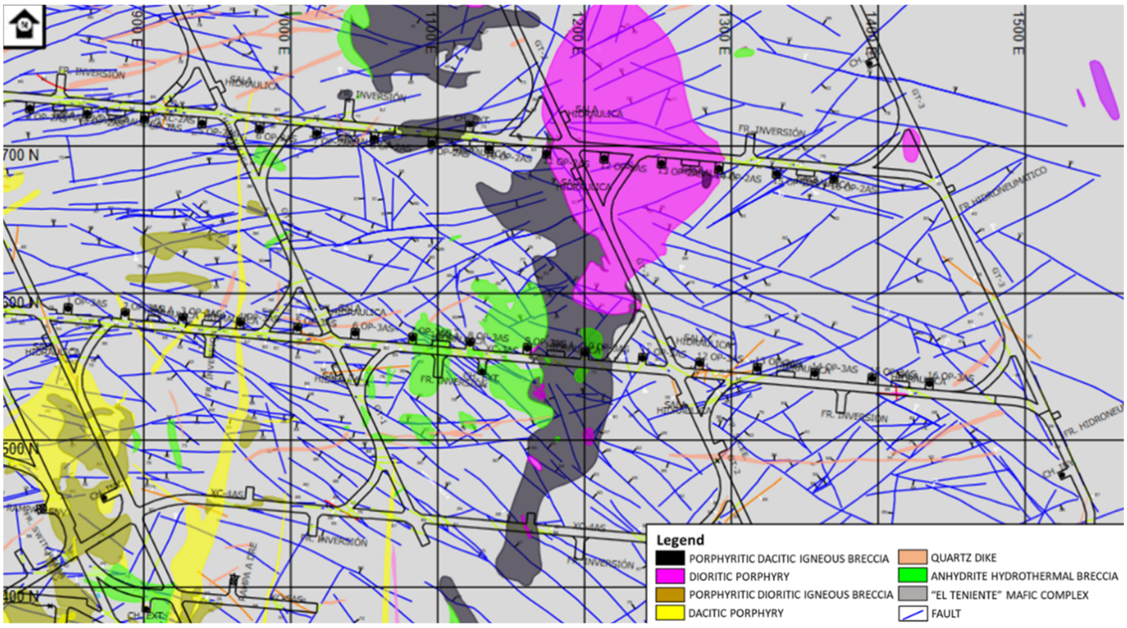


Figure 1 Lithological drawing and haulage level of the Andes Norte footprint (Codelco 2023)

2.1.2 Structures

In the primary rock of the Andes Norte project several types of geological structures are recognised, including faults, stockwork-type veinlets and fractures. Apart from fractures, all these structures feature varying mineralogical associations as infill, as depicted in Figure 1.

2.1.3 Stress present in the Andes Norte footprint

It is essential to know the stress field that prevails in the Andes Norte footprint in its pre-mining step so as to estimate the conditions to which the shaft excavations will be exposed. At the project, stress measurements have been made using acoustic emissions techniques (microseismicity) and hollow inclusion tests in the sector. Magnitudes for the major principal stresses are in the range of 55 to 60 MPa. Additionally, information from drillhole breakouts and the mine-scale model of El Teniente were used to enhance the reliability of the estimates in terms of the orientation of the principal stresses.

Due to the high mountain conditions towards the east sector (column height), as well as the exploitations of higher levels, a configuration that would explain the reason for high stresses on the eastern edge is generated (Figure 2).

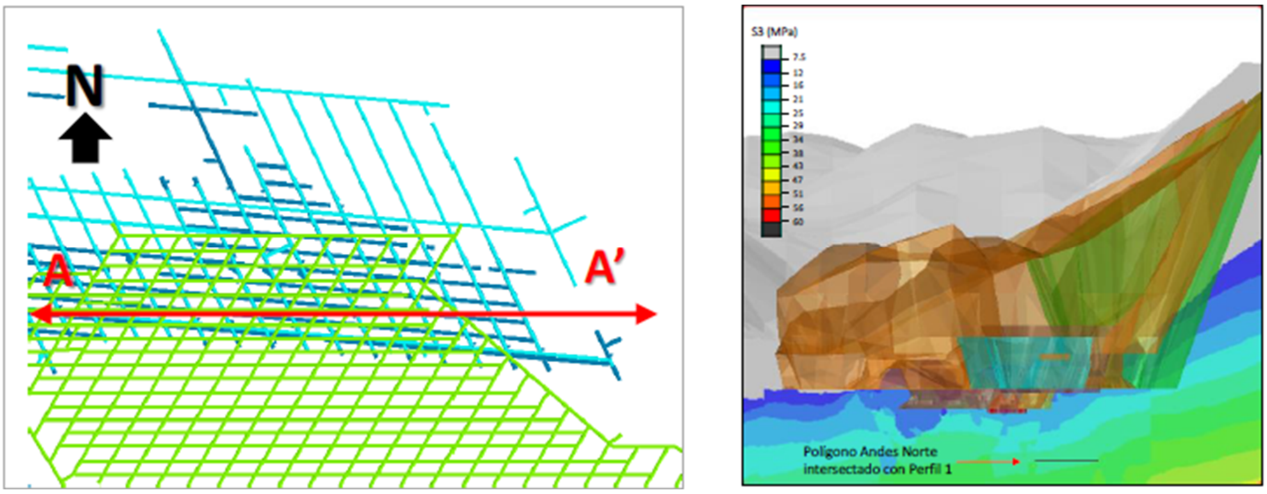
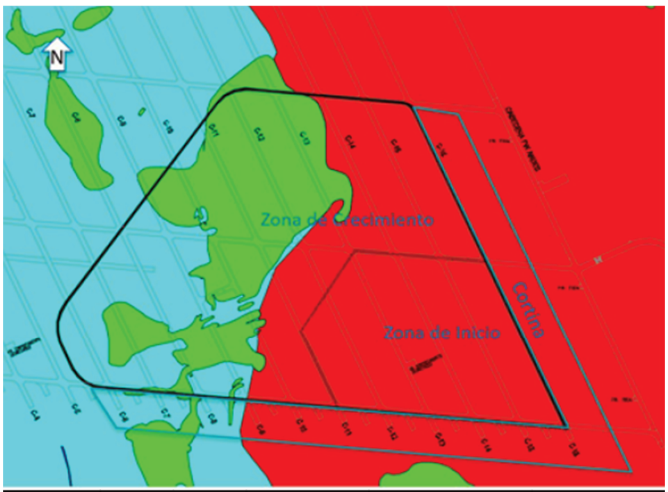


Figure 2 West–east section where the high mountain condition is specified in the east, condition for cavities 2017 (mine-scale model, Codelco 2017)

2.1.4 Denomination of geotechnical areas

Based on studies of the occurrence of soft veinlets, a classification of areas is provided in terms of the type of fragmentation (for the exploitation process through caving) and quality of the rock mass, which is inversely proportional to fragmentation. Below is the geotechnical zone classification model and a classification table of these corresponding to the Andes Norte footprint (Figure 3).



Color	Geotechnical Unit		Relative Sinking	Relative Fragmentation	Geotechnical Quality
	Roca Primaria	Zone 1	Very Bad	Very thick	Very Good
		Zone 2	Bad	Thick	Good - Very Good
		Zone 3	Regular	Regular	Good - Very Good
		Zone 4	Regular - Goog	Regular	Regular - Good
		Zone 5	Good	Fine	Regular
	Secondary Rock		Very Good	Very Fine	Very Bad

Figure 3 Geotechnical model at elevation 1887 undercutting level (Cifuentes et al. 2019)

2.1.5 El Teniente mining activities

Evidently, on a macro scale, the cavities generated from mining exploitation processes, specifically panel caving for mineral extraction at El Teniente, have influenced the stress state of the project. The footprint is specifically located beneath the Esmeralda and Pilar Norte mines, while the eastern sector, being situated in the projection of the exploitation edge, creates a very large pillar that increases the lithostatic pressure on it.

3 Objectives of using steel liner as shaft support

3.1 Shaft support in the production area

The exploitation method of the El Teniente mine is par excellence in panel caving and it will be employed for the exploitation of the new mine level. This is why the preparation tasks include the caving, production, ventilation and transportation levels. The ventilation level is connected to the different levels by ventilation shafts.

The shafts located in the exploitation area must be fortified to guarantee the safety and operation of the system. This is due factors including the following:

- Ventilation shaft stability — In panel caving, a large-scale ore extraction method is used and controlled fracturing occurs in the ore mass to allow its fall by gravity. This generates significant stresses and tensions on the shafts (abutment stress), which requires adequate support to maintain its structural stability. This is justified by the geotechnical environmental conditions of the Andes Norte footprint which were previously analysed.
- Prevention of rockfalls — During the caving process it is common for rockfalls and material movement from the shaft to occur, especially in the areas of greatest stress.
- Airflow optimisation — Ventilation shafts play a crucial role in supplying the mine with clean air while also evacuating gases and dust. Proper ground support helps to maintain the shape and integrity of the shaft, allowing airflow to circulate without obstacles. This is essential to ensure effective ventilation and maintain safe and healthy working conditions for personnel.

3.2 Installation of steel liner in the ventilation shafts as a rock support method

To choose the type of ground support to be used in a ventilation shaft, the different types of rock mass that can be found in the mine must be considered. For example, weathered rock tends to crumble due to lateral pressures.

There are always movements in the rock due to blasting and changes in stress, which generate risks of collapse in the shafts. To avoid rockfalls that could place people and equipment at risk, installation of a corrugated steel lining that guarantees the structural stability of the shaft is recommended.

This type of support has been successfully implemented in different mining projects—for example, Codelco Teniente and HMC Gold projects—where it has achieved fast, efficient and safe installation.

The use of shaft support with metallic corrugated pipe in the ventilation shafts of the Andes Norte project footprint responds to the variables of:

- Structural resistance — This is justified by the exploitation method to be used in the project. These shafts must be protected once the exploitation process has begun due to the variation of stresses induced by the transition zone (ZT) and so as to not affect the ventilation system of the project.
- Durability and corrosion resistance — Corrugated steel liner is designed to be durable and resistant to corrosion. In the mining environment, where there can be adverse conditions such as humidity, dust and corrosive chemicals, it is essential to use materials that can withstand these factors. Steel liners with anti-corrosion coatings (galvanised) or stainless steel are variably capable of withstanding these conditions and maintaining their structural integrity for an extended period.
- Installation efficiency — Installation of steel rebar in ventilation shafts can be done efficiently and relatively quickly. Steel liners are easy to handle and install compared to other support materials,

which can help to decrease construction times and minimise the impact on the overall mining operation.

- Cost-effective — The use of a steel liner for ventilation shaft support can be a low cost-effective solution compared to other support options. Steel liners are a widely available material and can be cost-competitive compared to other construction materials. Additionally, its long-term durability and corrosion resistance can result in lower maintenance and replacement costs over the life of the shaft.

As seen in Figure 4, overbreak of a post-excavated ventilation shaft has previously occurred, which justifies the installation of support in the shaft to prevent its loss.

Figure 4 Picture of a post-excavated shaft, Andes Norte, El Teniente (Codelco 2023)

4 Using a steel liner in the ventilation shafts of the Andes Norte footprint

4.1 Specifications of the steel liner coating and concrete filler

4.1.1 Galvanised steel liner

For the support of the shafts located in the Andes Norte footprint, installation of a galvanised steel liner with a diameter of 1,200 mm, a total length of 850 mm and an effective length of 750 mm per each ring (excavation diameter of 1,500 m) was considered due to the bolting and 5 cm overlap between each liner ring at the time of installation.

The theoretical length of the shafts excavated using the blind hole methodology, between the ventilation level and the production level, is 32 m. For this reason, these shafts (the most frequent type) have a total of approximately 44 corrugated rings (depending on the overbreak of the crown of the lower level) installed.

4.1.2 Concrete for filling the annular space

To fill the annular space between the steel liner and the excavated rock, self-levelling H40 (400 kg/cm^2 compressive strength) type concrete must be used. The theoretical amount of concrete fill is in the order of approximately 20 m^3, but this is affected (increasing its volume) by the existing overbreak in the shaft at the time that the concrete is cast. This depends on the type of rock, the mechanised excavation conditions and, in addition, the state of the rock mass after the hydrofracturing campaign.

In Figure 5, an example of the rock support system applied to the shaft of the Andes Norte footprint is shown.

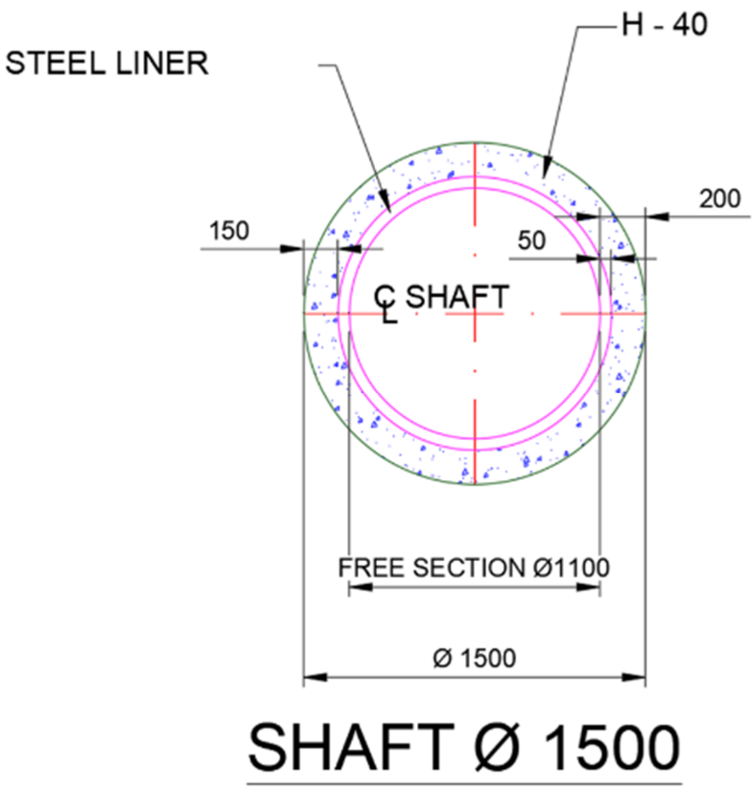


Figure 5 Rock support system, shaft, Andes Norte, El Teniente (Codelco 2023)

5 The construction process for the ventilation shafts

The excavation of shafts can be carried out by a conventional method or with mechanised excavation. In this project, a mechanised excavation was chosen due to its low cost, speed and safety.

5.1 Justification of the use of a blind hole machine for shaft excavation

The mechanised excavation methodology using a blind hole machine was chosen for the construction of ventilation shafts for the project to its advantages over other excavation methods.

- Precision: Due to its design and style of excavation, it allows precise excavation margins (although not as precise as the raise boring machine) to be maintained. Excavation and uninstallation times are faster than other methods. Therefore, it is the most efficient alternative.
- Safety: Use of a blind hole machine contributes to improving safety in the workplace. As an automated drilling method, it reduces workers' exposure to hazardous conditions and strenuous physical activities. In addition, its improved precision and control help prevent incidents and minimise the risks associated with excavating ventilation shafts.
- Less environmental impact: The blind hole machine can reduce the environmental impact compared to other excavation methods. Being a more controlled and precise process, the amount of excavated material and the waste generated are minimised. In addition, the technology used in these machines can incorporate dust capture and water recycling systems, helping to maintain a cleaner work environment and reduce the impact on ecosystems.
- Adaptability: Blind hole machines are highly adaptable to different conditions and types of terrain, including hard rock and soft soil. This makes them versatile and capable of facing diverse geological challenges, which in turn contributes to the efficiency and flexibility of the ventilation shaft excavation process.

5.2 Previous works required

To carry out excavation of the shaft efficiently and precisely, conditioning of the area where it will be located must be done. That is, the lower tunnel cuddy must achieve the following requirements:

- Definitive ground support installed without observations (with design dimensions required for the installation of the machine and equipment).
- The ground levelled by stencilling or final concrete slab sufficiently resistant to compression as it will be subject to compression by the blind hole machine at the time of excavation.
- Services installed for the excavation, such as electric power, an industrial water line, a drainage line and a compressed air line (for installation of equipment anchors), and a ventilation duct to the workplace.
- A pilot hole drilled prior to drilling for the use of the spearhead. Due to excavation difficulties, the installation of the spearhead in the tricone of the reamer was chosen. This spearhead is introduced in an ascending drilling from the lower level to the breakup level (upper), if it comes out in the place designed for a shaft break, and serves as a pilot hole for the blind hole, improving its precision and performance.

5.3 Mechanised excavation

Once the workplace has been prepared and the blind hole machine equipment has been installed, the shaft excavation begins with an excavation range between 1.8 to 3.0 m per shift, depending on the rock mass conditions in the area.

Upon completion of all excavation, the removal of drilling rods and the reamer, and disassembly of equipment, a safety cover is placed at the lower level of the shaft. This measure is taken to mitigate potential rockfalls from the upper level or within the shaft itself, thereby ensuring the protection of the workers.

The excavated shaft is then ready for the next process (shaft support).

Figure 6 Blind hole machine installed and waiting to start shaft reaming, Andes Norte, El Teniente

5.3.1 Examples of duration of shaft excavation processes

Below is a table detailing the duration times of the processes that make up the excavation of an example shaft from the ventilation level to the production level, with a total excavation length of 30.6 m. A graph (Figure 7) of total time percentages for each process is also presented, and the details can be viewed in Tables 1 and 2.

Table 1 Example shaft excavation process details (Codelco 2023)

Date	Shift	Process	Advance (m)	Process details
10/05/2023	Day shift	Installing	0	Installing machine and electrical services
	Night shift	Installing	0	Electrical services installation
11/05/2023	Day shift	Installing	0	Installing machine
	Night shift	Installing	0	Fixing the machine to the slab
12/05/2023	Day shift	Installing	0	Hydraulic unit maintenance
	Night shift	Reaming	1.2	Slowly reaming due to a shaft beginning
13/05/2023	Day shift	Reaming	0.6	Normal reaming
	Night shift	Installing	0	Rock collector installation
14/05/2023	Day shift	Reaming	0.6	Normal reaming
	Night shift	Reaming	1.2	Normal reaming
15/05/2023	Day shift	Reaming	0.6	Slowly reaming to prevent big rocks falling
	Night shift	Reaming	0.6	Slowly reaming to prevent big rocks falling
16/05/2023	Day shift	Reaming	1.8	Normal reaming
	Night shift	Reaming	1.2	Slowly reaming to prevent big rocks falling
17/05/2023	Day shift	Reaming	2.4	Normal reaming
	Night shift	Reaming	2.4	Normal reaming
18/05/2023	Day shift	Reaming	2.4	Normal reaming
	Night shift	Reaming	2.4	Normal reaming
19/05/2023	Day shift	Reaming	0.6	Slowly reaming to prevent big rocks falling
	Night shift	Reaming	2.4	Normal reaming
20/05/2023	Day shift	Reaming	1.8	Slowly reaming to prevent big rocks falling
	Night shift	Reaming	2.4	Normal reaming
21/05/2023	Day shift	Reaming	2.4	Normal reaming
	Night shift	Reaming	2.4	Normal reaming
22/05/2023	Day shift	Reaming	1.2	Normal reaming and breakthrough on upper level
	Night shift	Uninstalling	0	Machine rods removal from shaft
23/05/2023	Day shift	Uninstalling	0	Machine rods removal from shaft
	Night shift	Uninstalling	0	Machine rods removal from shaft
24/05/2023	Day shift	Uninstalling	0	Machine rods removal from shaft
	Night shift	Uninstalling	0	Machine rods removal from shaft
25/05/2023	Day shift	Uninstalling	0	Machine rods removal from shaft
	Night shift	Uninstalling	0	Safety cover installation and continued machine uninstallation
26/05/2023	Day shift	Uninstalling	0	Uninstalling machine
	Night shift	Uninstalling	0	Ending of the uninstallation of the machine

Table 2 Process duration summary table (Codelco 2023)

Process	Shifts	Days	%
BH installation	6	3	17.65
BH uninstallation	9	4.5	26.47
Interference	0	0	0
BH reaming	19	9.5	55.88

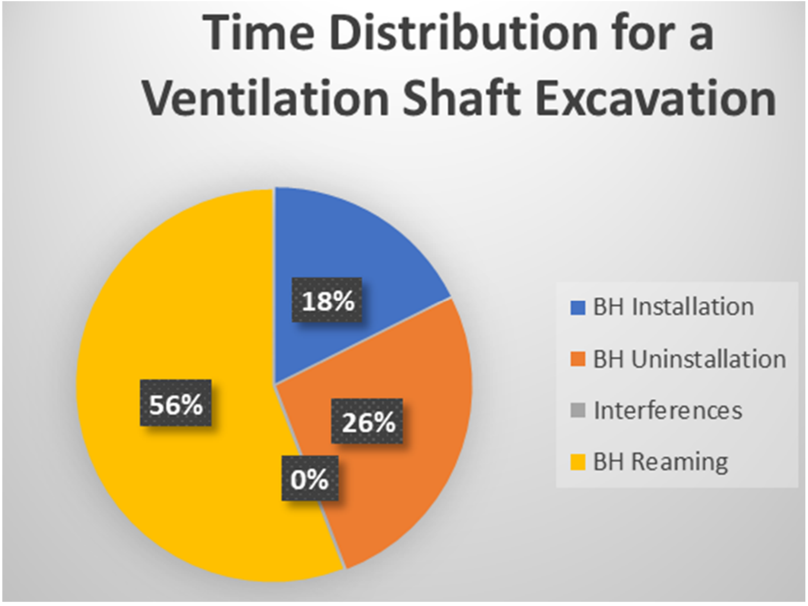


Figure 7 Process time distribution illustration (Codelco 2023)

5.4 Shaft support

The ground support process involves a series of preparatory works prior to installation of the steel liner and concreting of the annular space.

5.4.1 Preparations for installation of the ground support

For preparation of the upper tunnel cuddy, where the steel liner will be installed, work must be carried out to allow the efficient and safe assembly of the support with the required quality standard.

- Drilling of eye-type lifting bolts for steel cable installation and preparation of the safety line is required for the safety of personnel when working at the edge of an open shaft.
- Depending on the overbreak generated on the floor of the upper cuddy as a result of the breakthrough with the blind hole machine, levelling and improvement with concrete must be undertaken. This is creates an even surface for safety and efficiency in the ground support process. If the use of concrete is not possible, a safety cover using rigid materials such as wood for the platform and anchors to the rock must be installed.
- For preparation of the lifting base, the axis of the shaft must be set out according to the breakthrough point on the roof of the upper level cuddy of the shaft. With this consideration, the anchors are drilled and installed for the preparation of the base for lifting manoeuvres and/or delivery of necessary accessories for the installation of liners.

5.4.2 Steel liner installation

Once the preparation tasks have been completed and the work area has been prepared, the installation of the rings that make up the liner starts. For this operation, a repetitive task is executed which consists of the following stages:

- Installation of liner holder or liner base — Installing and hooking from the lifting base to the liner holder, and this can go down along the shaft. It is important that the choice of lifting accessories for the installation of the liner is appropriate, depending on the length of the liner column length and the total weight to be supported (Figure 8).

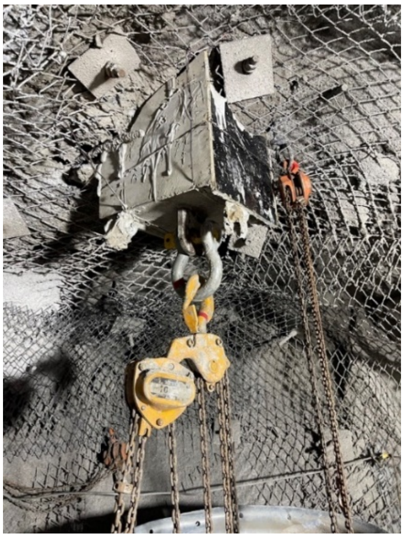


Figure 8 Lifting base for liner installation, Andes Norte, El Teniente

- The liner ring that is installed is conformed by three pieces joined together by bolts, forming a ring with a diameter of 1,200 mm in the wide part and 1,160 mm in the narrow part. The length of this ring set is 850 mm in total, but its effective length, due to the bolting overlaps with the next ring set, is 750 mm.
- Once assembled, the joint ring is installed on the liner holder and lowered into the shaft.
- The next set of rings is assembled on top of the previous set, piece by piece. When the process is finished, the complete set is lowered with a lifting key and liner holder (Figure 9).

Figure 9 Steel liner column installation process, Andes Norte, El Teniente

- This task is repeated until there is confirmation that the liner column reaches the lower level, where the security cover then the removal of the blind hole must be removed.
- The total number of sets of liner rings installed depends on the overbreak of the roof of the lower cuddy. For a shaft with a 32 m theoretical length, such as those for ventilation between the ventilation and production levels, the average number of liner rings installed per chimney is 44.

5.4.2.1 Example of the duration of installation of metallic corrugation in ventilation shaft

An example case of steel liner preparation and installation times is presented for a ventilation shaft of 30.6 m long with a total of 41 units of corrugated rings. Tables 3 and 4 show the details of process times. Figure 10 shows their percentages.

Table 3 Shaft liner installation process details table (Codelco 2023)

Date	Shift	Process	Advance (liner)	Process details
06/06/2023	Day shift	Preparation	0	Construction of safety steel cable line
	Night shift	Preparation	0	Security cover construction
07/06/2023	Day shift	Preparation	0	Construction of lifting base
	Night shift	Preparation	0	Construction of lifting base
08/06/2023	Day shift	Preparation	0	Installation of lifting accessories
	Night shift	Liner installation	1	Finishing preparation and installation
08/06/2023	Day shift	Liner installation	3	Installation
	Night shift	Liner installation	4	Installation
10/06/2023	Day shift	Liner installation	6	Installation
	Night shift	Liner installation	5	Installation
11/06/2023	Day shift	Liner installation	6	Installation
	Night shift	Liner installation	7	Installation
12/06/2023	Day shift	Liner installation	6	Installation
	Night shift	Liner installation	3	Installation

Table 4 Liner installation process times summary table (Codelco 2023)

Process	Shifts	Days	%
Preparation	5	2.5	35.71
Liner installation	9	4.5	64.29
Interferences	0	0	0

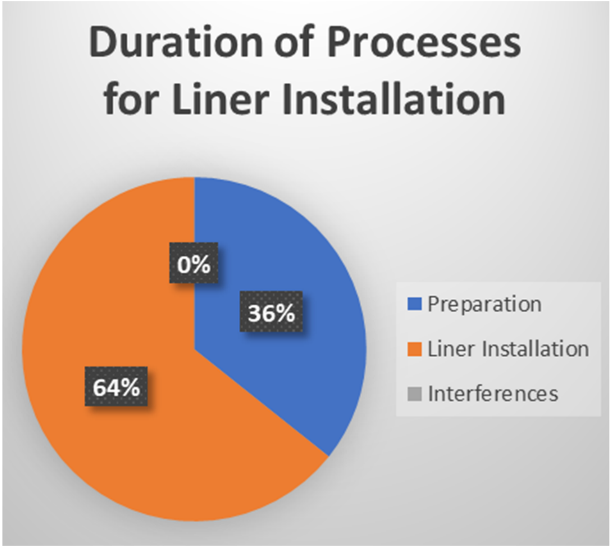


Figure 10 Timing distribution illustration

5.4.3 Filling of annular space with self-levelling concrete

When concluding with the installation of the entire steel liner in the shaft, the stage of filling the annular space between the shaft and the steel liner with self-levelling concrete begins.

- Prepare the concrete cast — Installation of the covering is carried out at the lower level of the annular space, between the contour of the shaft excavation and the liner column, using superimposed mesh in order to reduce the holes from which the concrete can leak.
- Plug concrete cast — H40 type pumpable concrete is slowly casted (for this type of ventilation shaft) as a plug around the liner column. The lower level is observed in the same way, in search of concrete leaks. If no leaks are detected for repair at a lower level, it is filled with self-levelling concrete of the same compressive strength.
- If there is a leak that cannot be sealed by installing mesh in the annular space, shotcrete is used as a seal for lower level projection in the leak sector.
- Self-levelling concrete cast — the entire annular space of the shaft must be filled with self-levelling concrete with a resistance of 400 kg/cm^2 to compression. This filling is carried out until it reaches the height of the final slab of the upper level or, in this case, of the production level.

The duration of the casting process will clearly depend on the overbreak present within the shaft that must be filled with concrete. The availability of the batching plant for delivery of the concrete at the workplace must be also considered.

With the completion of this task, the support of the ventilation shaft between the ventilation level and the production level is considered complete.

5.5 Remaining work for the rehabilitation of the ventilation shaft

The remaining works to ensure that the ventilation shaft is structurally safe include:

- Provision of a concrete foundation base on which infrastructure can be installed, according to the type of ventilation shaft (air injection or extraction).
- Installation of a fan or extractor, depending on the type of shaft, and a 90° pipe elbow to direct the airflow to the liner column.

- Installation of a safety cover on the upper level of the shaft cuddy, comprising a wall no higher than 500 mm from the production level and a metal grill that prevents entry of personnel to the shaft but ensures airflow through it.

6 Lessons learned

The construction process for the ventilation shafts at the Andes Norte Nuevo Mine Level project was not exempt from setbacks and interferences (with other works) that reduced its performance. These included construction and operational difficulties due to the conditions of the rock and the workplace. Based on this, work techniques and methodologies were developed that helped improve performance, reduced downtime and eliminated waste in order to work in an environment of continuous improvement. These included:

- Improvements in work prior to excavation — Work was undertaken in conjunction with field planning for constant evaluation. With this, the waiting times for the mechanised excavation team (blind hole) for the next workplace were eliminated by anticipating the preparation works in the lower cuddy of the ventilation shaft (where the equipment was installed) and, in this way, receiving the equipment on time.
- Implementation of the pilot hole for the blind hole — Due to deviations in the shaft excavation with the blind hole due to rock mass conditions, a metal spearhead was installed in the middle of the tricone of the reamer (as shown in Figure 11). To make use of this, pilot hole drilling was carried out with Simba jumbo top hammer drilling equipment. Once pilot hole breakage was verified with acceptable parameters, the reamer lance was delivered and aligned to this hole. This considerably decreased the deviations of the shafts, thereby improving the quality and performance of the fortification.

Figure 11 Spearhead tricone installed on the blind hole rig reamer, Andes Norte, El Teniente

- Retaining personnel and increasing tools — During this time, it was agreed that trained personnel who had been working on installation of the shaft steel liners would continue permanently with this type of work. This was to ensure that their learning curve was not lost. They were also provided with a greater number of tools (including a torque gun), which had a significant impact on the speed of the steel liner installation.

7 Conclusion

This document presents the development and implementation of a methodology for reinforcing ventilation shafts in the Andes Norte NNM project. In this regard, the following conclusions can be drawn:

- The development of the ventilation shafts in the Andes Norte project took place in an environment characterised by high stresses and anisotropy, necessitating the construction of fortified shafts from the ventilation level to the production and sinking levels. The methodology described in this paper addresses this requirement.
- During the execution and implementation of this methodology, various operational problems specific to each shaft were observed and detailed in this document. Some recurring issues encountered during construction included guide tube deflection, over-excavation and the collapse of coarse material, among others.
- As part of the shaft development process, and considering the geotechnical characterisation of the project, a piloted reaming process was implemented to prevent shaft deflection.
- The successful implementation of shaft support is a result of the collaborative efforts among different cross-functional areas involved in the shaft development operation. This approach aimed to create a novel construction methodology.

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