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From the long term planning to the operation. The role of the hydrogeological strategic plan for a large open pit

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Abstract

The importance of a proper hydrogeological strategic plan in a massive open pit operation is critical considering the deepening of the pits, which implies large and high slopes increasing the pore pressure resulting in potential slope instabilities and dewatering challenges for operating. In the life of mine planning cycle the hydrogeological condition must be incorporated from the uncertainty of the conceptual model to the dewatering day-to-day operation. In the case of Escondida Asset the strategic plan starts from a proper understanding of the hydrogeological conceptual model and uncertainties which conducts to a hydrogeological characterization plan as part of the life of the mine inputs; the results of numerical model for pore pressures to focus on the depressurization targets, which define the depressurization drilling campaigns and the short term activities; the consideration in the mine design, as a part of the mine plan, for depressurization and dewatering issues; and finally, the day to day control for dewatering. Normally, the dewatering strategic plan considers several cases as a sensitivity problem for slope stability and drainage issues. The added value of hydrogeological strategic plan is basically improving the reliability of the mine plan from the long term to the operation and develop de-risking for the business plan. With a proper understating of the hydrogeological issues through the years of the mine plan, avoid having non-planned problems impacting the operation and the planning process. Also is relevant the link and synergy that the hydrogeological strategic plan establishes between different disciplines, specifically, with structural geology and geotech who is basically one of the most important inputs for the large and massive open pit operation in the context of high pore pressures for the slopes and dewatering issues considering the hydrogeological strategic plan as a continuous improvement process aligned with the mine planning cycle.

1 Introduction

Hydrogeological characterization, studies and analysis that support the design of appropriate dewatering and depressurization systems for operational water management and decrease of the risks related to pore pressure, represent an important component for the execution of mining plans (Read & Beale 2013) and the analysis and optimization of the geotechnical design of the mining slopes, when the hydraulic condition has a significant impact in the stability (Read & Stacey 2009).

The estimation of the water outflow flows inside the pit based on the progress of the mining plan is key to an adequate design of water extraction systems that allow to keep the operation safe and without interruptions. Similarly, hydrogeological studies and in situ monitoring have allowed the estimation of the effectiveness of depressurization systems in reducing pore pressure and thus contributing to the stability of the slope.

The incorporation of hydrogeological knowledge in the planning and operation processes allows minimizing and mitigate the risks from the long term through the concept of safety by design, capturing value by optimizing slope angles and ensuring the ore extraction during the mining operation, minimizing the impact of water in the processes of ore extraction, crushing and processing.

To meet these objectives, and like most of the water management problems, it is necessary early planning and adequate monitoring of the dynamic conditions of hydrogeological systems, characterized by a transitory behavior conditioned by different variables, both natural (recharge, storage capacity, evaporation) and artificial (efficiency and availability of extraction systems).

This transitory condition, and its integration with mining plans, requires proactive and flexible planning, technical work connected with other disciplines and areas, such as geotech, structural geology, geophysics, mine planning, well hydraulics, water well drilling, among others, as well as the influence and communication skills of the specialists, that ensure an adequate integration of all areas involved for the achievement of the objectives.

2 Integration of hydrogeology in the mine planning cycle

Minera Escondida Limitada (MEL), as part of its annual planning process, develops slope stability geotechnical studies in its two open pit operations, which include Escondida mine and Escondida Norte mine.

Simultaneously, hydrogeological studies are carried out focused on understand and represent the distribution of pore pressures in the current pit slopes and in their future geometries, as well as to estimate the water flows that will enter the pit according to the development of the pushbacks considered in the mining plan.

There is a workflow integrated with the mine planning cycle (CAP cycle) to optimize the design of existing monitoring, dewatering and depressurization systems, in a process of continuous improvement (Figure 1), based on a better knowledge of the effects of dewatering and depressurization in the pit, acquired in the following processes:

- Hydrogeological numerical modeling
- Integration between the hydrogeological results and geotechnical stability and operational condition, embedded in the planning cycle
- Definition of depressurization and dewatering targets and metrics based on the pore pressure influence in slope stability and water interference in mining operation
- Review of depressurization and dewatering targets compliance through continuous monitoring of the hydrogeological variables

The activities of this design and verification process are specified in the dewatering, depressurization and monitoring plan of each mine, documented in the "Integrated Plan".

This Integrated Plan includes the location and technical design of the required works for the dewatering and depressurization in both pits, in order to ensure the development of the mining plan, avoiding impacts related with geotechnical stability and operational interference. This document, updated yearly, includes a five-year drilling program with monthly granularity during the first two years, and the definition of the hydrogeological targets for each of the elements considered in the plan.

These hydraulic elements are simulated in the hydrogeological and geotechnical numerical models that allow predicting the response in terms of dewatering and depressurization, and evaluating the impact on operational and stability conditions in the pit. This plan is updated annually according to the current LoA (Life of Asset) mining plan, adapting the targets and verifying its compliance through the monthly monitoring and quarterly reports.

The verification of the compliance of these targets, results in an analysis of causes and impacts of a deviation from the expected values, in order to propose mitigation plans for each one of the main causes identified, to be incorporated into the plan design (optimization) and plan execution (operational).

An annual report compiles all the analysis, studies and plans developed during the planning process, in each of its design stages, which are defined below:

- Conceptual Plan: establishes the general dewatering and depressurization targets and propose a preliminary drilling program of drains, pumping wells and monitoring wells, focused on the medium and long term, which is numerically simulated to project the hydrogeological effect.
- Optimized Plan: collects the results obtained through the previous numerical simulation and propose an improved drilling program, focused on the medium term, which allows to optimize the dewatering and depressurization effect in critical areas from the point of view of operation and slope stability.
- Executable Plan: adjusts the drilling program into an operational plan, focused on short-term activities, and propose an annual detailed drilling program.

In addition, this annual report includes the analysis of the compliance of the dewatering and depressurization targets defined in the Integrated Plan developed the previous year, which allows a continuous improvement of the conceptual understanding of the system, from a hydrogeological and geotechnical point of view, based on the analysis of the following points:

- Analysis of the compliance of the drilling campaign (drains, piezometers and pumping wells) according with the Executable Plan of the previous year, considering physical (meters) and spatial (position) compliance.
- Analysis of the monthly data collected in the piezometers and verification of the compliance of the dewatering and depressurization targets, according with the absolute decreases obtained from the numerical hydrogeological modeling of the Optimized Plan, for each piezometer sensor of the monitoring network.

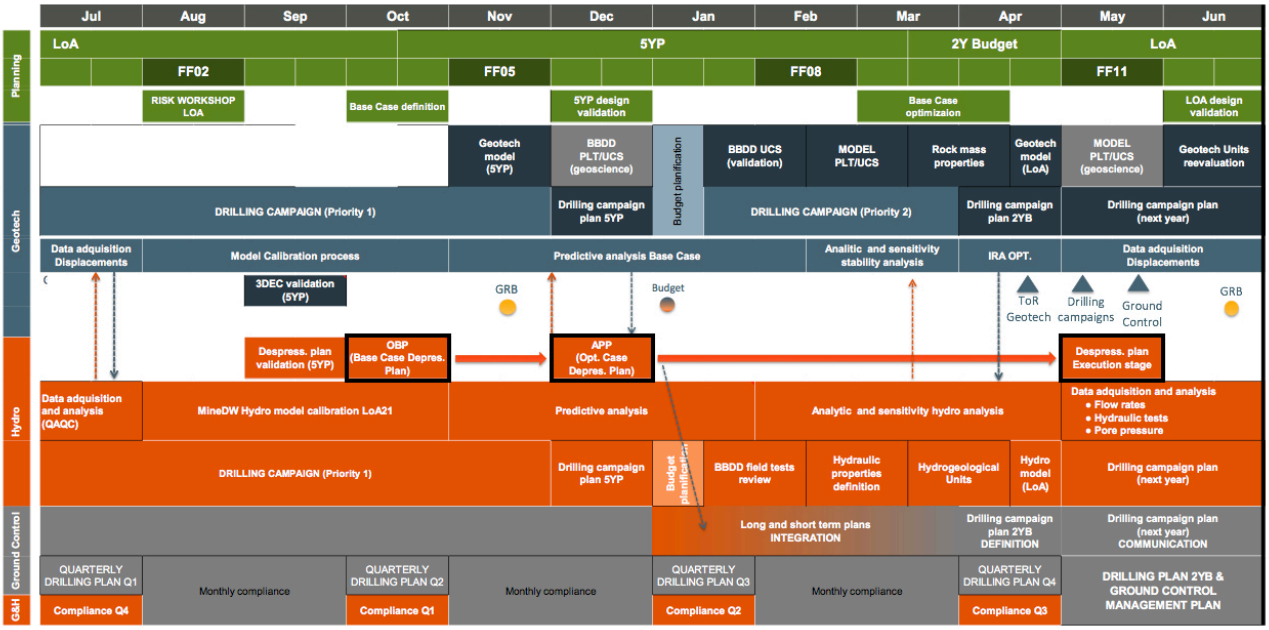

Figure 1 **Integration of mine hydrogeology in the annual mining planning cycle, showing the three stages of the depressurization plan**

2.1 Conceptual and numerical hydrogeological models

Minera Escondida currently has hydrogeological conceptual models for both pits, Escondida and Escondida Norte, which are updated and fed back annually with all the new information captured during the yearly drilling campaigns, piezometric monitoring data and hydraulic tests results.

In addition to the hydrogeological data captured in the field these conceptual models are supported by geological models (lithology, mineralization and alteration), structural and geotechnical models, looking for correlations in the behavior of materials from a hydraulic and geomechanical point of view.

The integration of the disciplines related to geosciences and engineering in the analysis and interpretation of the operation of groundwater systems under intensive hydraulic stress, such as the execution of mining plans in open pit mines, is a key driver for the correct definition and achievement of the dewatering and depressurization targets.

Figure 2 shows the spatial distribution of the fracture frequency (FF) and the main structural system of the Escondida pit, and the piezometric monitoring network that feed the acquisition of pore pressure data that support the conceptual models and hydrogeological analysis.

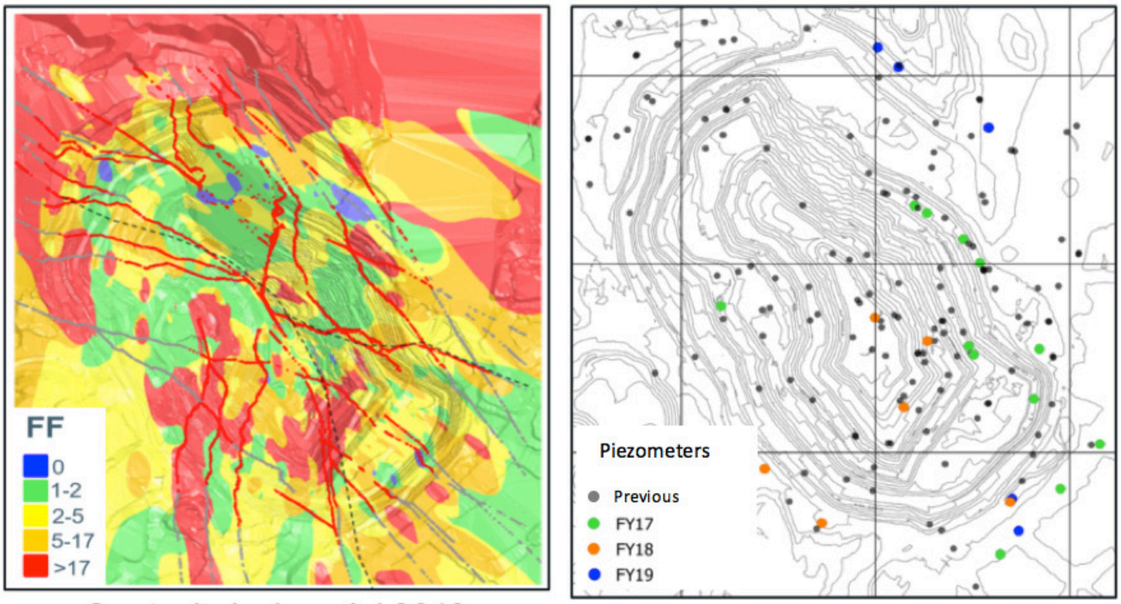

Figure 2 Geotechnical and hydrogeological information that supports hydrogeological analysis

The conceptual models are implemented in a hydrogeological numerical tool, whose main objectives are: to simulate the effect of the proposed integrated dewatering and depressurization plans, analyzing opportunities to improve the efficiency of the system; to obtain a projection of the pore pressure behavior and depth values of the water level in the walls and the bottom pit, according to the evolution of the mining plan; and to establish the targets of dewatering and depressurization that will ensure the operation and slope stability.

Also, an adequate use of the numerical tools allows to implement sensitivity analysis of the slope stability to the pore pressure, in order to increase the understanding of the influence of the pore pressure as a conditioning mechanism of instability.

Furthermore, the numerical tool helps to calibrate the hydraulic parameters of the materials based on the results of the available hydraulic tests and to identify sectors of data uncertainty, that support the design of the drilling campaigns to capture hydrogeological information and increase the monitoring network.

Figure 3 shows the latest advances in the hydrogeological understanding of the conceptual and numerical models of both pits, as part of a continuous improvement process aligned with the mine planning cycle.

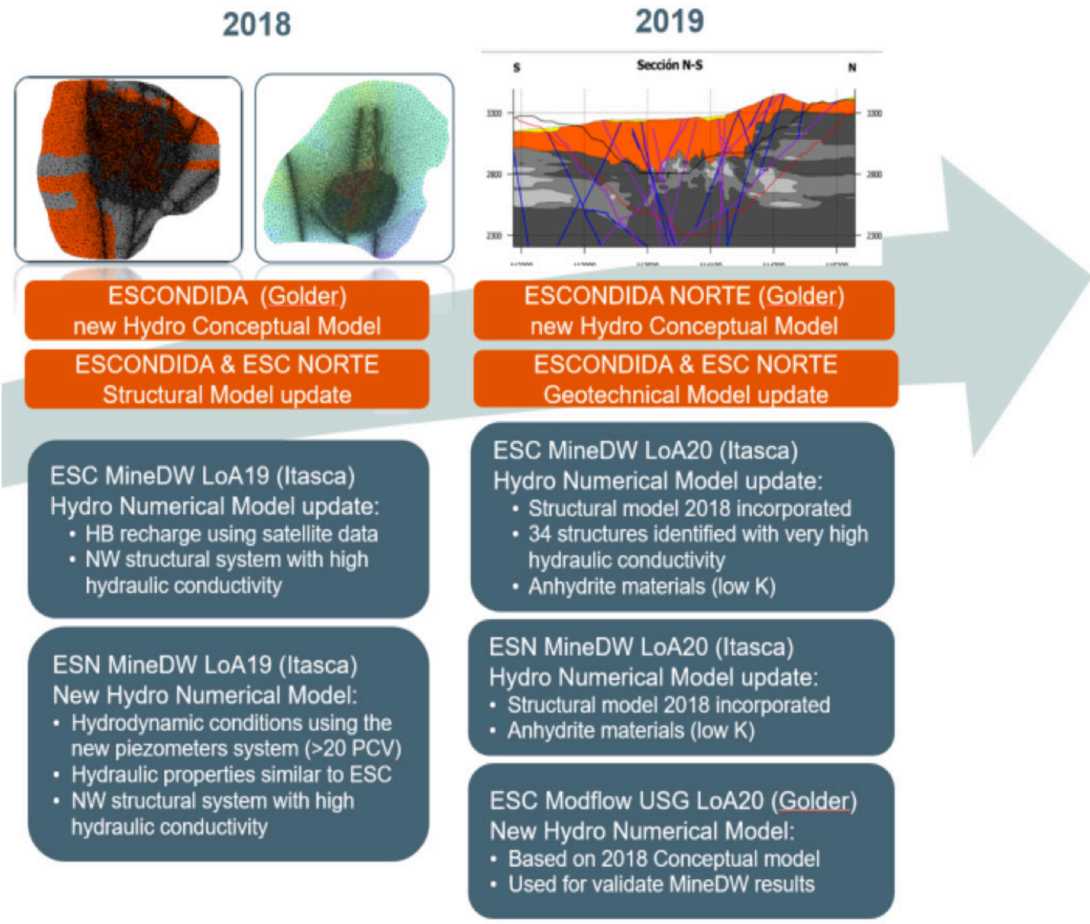

Figure 3 **Development of the conceptual and numerical models of both pits during the last two years**

2.2 Integration of hydrogeological and geotechnical results

The numerical hydrogeological tool used has been the Itasca MineDW program, a 3D finite element groundwater code, which exports pore pressures in formats compatible with other slope stability geomechanical models (3DEC).

The period of calibration of the model includes from the beginning of the mining operation until the data of June of the current year, and considers all the historical information of pumping wells, drains and monitoring wells.

The simulation period begins in July of the current year and is projected until the end of the mine's life according to the mining plan. The simulation scenarios include the Conceptual and the Optimized Plans, with monthly positions for each hydraulic element during the first two years and yearly positions for the next five years, and it is projected until the end of the mine's life with 5-year time steps, considering a dewatering and depressurization system through drains and pumping wells. The simulation scenarios also consider the study and evaluation of other dewatering and depressurization alternatives using different methodologies and/or technologies.

The model exports the drawdown isocurves obtained by the execution of the drilling campaigns for drains and pumping wells, that allow to create the depressurization bulbs associated with the proposed system, in order to verify the effectiveness of the proposed dewatering and depressurization system, and identifying sectors where there is a potential opportunity for improvement in the system design.

For example, Figure 4 shows a comparison of the results obtained by both, the Conceptual and Optimized plans throughout the five-year period. The picture shows the depressurization bulbs, it means, the isosurfaces with the same depressurization effect, from a lower (blue color) to a higher effect (yellow color), as a consequence of the horizontal drains (grey and red straight lines).

Based on the depressurization results of the Conceptual Plan simulation (stage 1 of the design process), the proposed drains for FY21 in the Northeast wall were discarded, since they did not show a depressurization effect that justified its construction. Analyzing the causes of this low performance, for that year those drains were at a very similar position than the water table in the sector, so the design of the drains of the east wall was modified, looking for the optimal configuration to maximize the depressurization effect.

The results obtained with the Optimized Plan proposed after reviewing the Conceptual Plan simulation (stage 2 of the design process), shows how the modifications lead to a notable improvement in the depressurization effects obtained with the numerical tool, based on optimizing the location of drains.

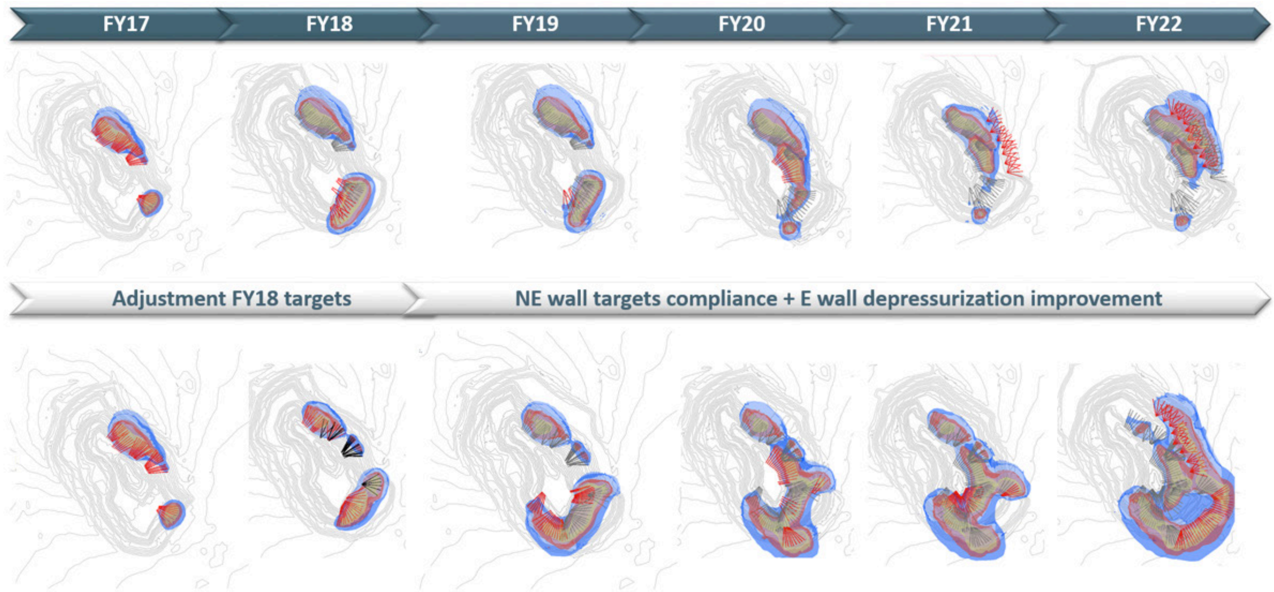

Figure 4 **Comparison of depressurization effects of stages 1 (Conceptual Plan) and 2 (Optimized Plan)**

The pore pressure obtained from both hydrogeological simulations are used as an input for the stability conditions analysis, allowing to identify those sectors in which the hydrogeological condition has an effect on the slope factor of safety.

The geotechnical numerical tool used has been the Itasca 3DEC software, a 3D code for geotechnical analysis of rock, that simulates the response of discontinuous media, such as jointed rock under load, that allows to incorporate the intersection of structures.

The location of the drains has been prioritized in those areas where the factor of safety (FoS) is below 1.2 and where the current understanding of the failure mechanisms makes it possible to assume a clear influence of the pore pressure as a conditioning agent for the triggering of a geotechnical event.

2.3 Definition of depressurization and drainage objectives, compliance verification and cause analysis

Once the design of the Dewatering and Depressurization Plan is optimized to obtain the best design and location configuration for the hydraulic elements, ensuring the highest system efficiency in terms of lowering pore pressures and water level, the following targets are established:

- Drilling target: physical and spatial compliance, in terms of meters and position, of the Integrated Monitoring, Dewatering and Depressurization Plan, that includes piezometers, sub-horizontal drains, observation wells and pumping wells.
- Depressurization targets: decrease in pore pressure mainly associated with the construction of sub-horizontal drains and the progress of the mining plan.

- Dewatering targets: cumulative decrease of the piezometric level below the pit surface mainly associated with the operation of a system of extraction wells.

The depressurization and dewatering targets are defined for each of the existing sensors in the vibrating wire piezometers that belong to the monitoring network of both pits, for the entire five-year period, and are compared monthly with the measured data in order to validate the model and analyze the causes of the potential deviations identified.

Thereby, each of the available sensors, several comparison graphs are constructed to identify and understand the differences between the projected targets and the actual data obtained in the field:

- Accumulated depressurization projected by the model and observed in the field, in pressure units (mca) over time, to observe the response of the system
- Variation in depressurization rate over time to analyze the influence of the construction of nearby hydraulic elements
- Graphics that show the spatial distribution in both pits of each VWP (vibrating wire piezometer) sensor using a color code according to the compliance of their depressurization targets to identify risk areas

Simultaneously to the verification of the targets compliance, the potential causes of deviation in areas with similar behavior are analyzed, in order to improve the understanding of the hydrogeological system and to establish mitigation plans (monthly and quarterly) to correct the identified deviations and to achieve the projected targets for the complete year.

According to the historical operation of the Escondida dewatering and depressurization system, three main causes of the potential deviations from the depressurization targets have been identified:

- Decreased efficiency of dewatering and depressurization system due to operational or maintenance stops or failures.
- Differences in the execution of the planned dewatering and depressurization program established in the drilling plans.
- Uncertainty in the hydrogeological conceptual and numerical models.

Each of these causes generates the activation of specific actions focused on both, short and long term, such as the restoration of the operation of pumping wells that may have been stopped, the intensification of the number of drains in a sector where the depressurization results are lower than expected, or the increase in the number of monitoring points and the execution of hydraulic tests in sectors with hydrogeological uncertainty to improve the results of the simulations.

3 Learnings and challenges from safety by design to operational discipline

As a result of the implementation of this methodology in the operation of Minera Escondida during the last three years, and based on the experience acquired, several key aspects have been identified for an adequate integration of hydrogeology within the planning and operation mining process.

One of the most relevant aspects for the compliance of the targets is related to an adequate organizational structure that facilitates communication and collaboration between the work teams, with the specific targets of each area of planning and operation clearly established and inter-related, and with the resources necessary for the development of the critical activities for the achievement of the whole process, from the capture of data in the field, the analysis of the information, a correct process for planning and execution of the drilling campaigns, the pumping wells assembly and commissioning, the extraction of the water from the bottom of the mine and the operational water management.

It is follow from above that a good communication of the risks related to the non-compliance of the depressurization and dewatering targets is required, ensuring that water management is maintained as part of the day-to-day mining operation and that all parties involved in the process collaborate consciously in the common objective of maintaining a safe operation.

One of the main challenges is to ensure a continuous flow in the development of depressurization and dewatering plans from the long term to the execution stage, proposing drilling campaigns integrated into the mining designs, allowing the drains, pumping and monitoring wells construction in those sectors where it is really necessary. Regarding this point, the term "depressurization and dewatering berm" has recently been incorporated in Minera Escondida, captured into long-term designs, which ensures the necessary spaces for drilling wells and drains in areas of difficult access, considered critical from the point of view of depressurization and water extraction.

A key aspect to communicate the relevance of this type of considerations is the evaluation and comparison of the impacts on production as a consequence of the design change incorporating this berm, with the impacts generated by the interference of water in the sector in the case of not be included.

The availability of adequate machines for the execution of the proposed drilling plans, adapted to the space restrictions of a pit, and ensuring the company's safety standards, is a key aspect that must be captured from an early stage in the hiring process, incorporating the technical requirements necessary for an adequate fullfilment of the targets.

Finally, having an adequate and continuous monitoring network with continuous and real-time operational reports of the field data, with a robust validation and quality assurance system (QAQC) is determinant for an adequate analysis of the information, improvement of hydrogeological understanding and its impact on geotechnical behavior, taking special relevance for decision-making from both, an operational and business point of view.

4 Conclusions

Historically, water has generated impacts on mining operations worldwide, including instabilities associated with an increase in pore pressure in materials where it acts as a conditioning factor of a failure mechanism; impacts on mining plans compliance due to operational delays caused by the presence of water at the bottom of the pit; and impacts on material handling during the process of extraction, grinding and treatment of the mineral due to moisture.

One of the main challenges of water management in the mining operation is to embed hydrogeological knowledge in the operation, ensuring an adequate water management by all the teams involved, from the earliest stages of design to drilling and assembly of the pumping wells, including the execution of engineering works that continuously extract the water from inside the pit.

Mine planning must also deal with the dynamic and transitory nature of water, conditioned by different variables, generally dependent on different work teams and subjected to rigorous operational discipline.

The integration of the hydrogeological discipline in the formal processes of planning and mining operation, strengthened by an adequate capture of data in the field to decrease technical uncertainty, supported by the existing geological, structural and geotechnical information, governed by a work cycle that ensures the participation and involvement of all the accountable teams, with adequate communication channels and skills, has proven to be able to minimize the risks associated with water management and hydrogeological uncertainty.

Once risks are controlled, water management in mining operations is able to move to an optimization stage, in which value for the business is captured by optimizing designs (for example, increasing the inter-ramp angle in sectors in which the pore pressure is a determining factor for the stability of the walls); in which water is operationally managed in such a way that water losses by infiltration and evaporation are minimized and water reuse is maximized, ensuring the water resource along time; and in which the moisture content is used as a variable controlled from the source in the mineral extraction, milling and processing processes.

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