

Cave back evolution monitoring and evaluation of criteria to support extraction strategy, Pilar Norte mine El Teniente division Codelco Chile

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ABSTRACT

Until 2021 in El Teniente mine, we used two methods to directly verify the cave back geometry. 1) tunnels inspection at upper levels intersected by the collapse process, 2), analysis of the recovered core of long holes towards the cavity. Some limitations with these methodologies were due to the low or non-existent availability of tunnels at higher levels and the low drilling frequency of long holes for this purpose.

This document presents a case study, focused on the periodic monitoring of cavity evolution and its relationship with the area incorporation and ore extraction in the Pilar Norte Mine.

The main objectives of this study are the periodic monitoring of the cavity evolution relating it to mining activity, to determine a collapse criterion based on sensor displacement rate.

The installed instrumentation not only allows measuring the limit of the collapse, but also makes it possible to determine the area prone to collapse before it occurs. To this end, the retrospective analysis of the disconnected devices has made it possible to establish thresholds in the movement rate established by these zones.

In addition, a connection is established between mining activity and disturbances in the devices along the instrumented wells. This technical development already takes a period of two years of important data collection.

1 PILAR NORTE CONTEXT

Pilar Norte corresponds to one of the mines currently in operation in the northern sector of El Teniente Division (see Figure 1). It has an approximate production of 6 [kt/d] with an average grade of 1.3% CuT.

In geometric terms, its location stands out between the Esmeralda and Reservas Norte cavities (see Figure 2), a condition that generates a concentration of stresses in the exploitation polygon, reaching 60 and 30 MPa as the major and minor principal stresses, respectively.

The mining method corresponds to Panel Caving in its variant “Bateas Altas” with Hydraulic

Fracturing. Considering that Pilar Norte is the southern extension of the Reservas Norte cavity, it is expected that in the future the connection between the Esmeralda and Pilar Norte cavities will materialize, leading to a decrease in stresses in the sector and, consequently, a lower risk of rock burst.

Based on the above, in 2021, the instrumentation of Caving monitoring was implemented to measure the growth of the Pilar Norte cavity towards the south, complementing the information that will confirm the connection of cavities.

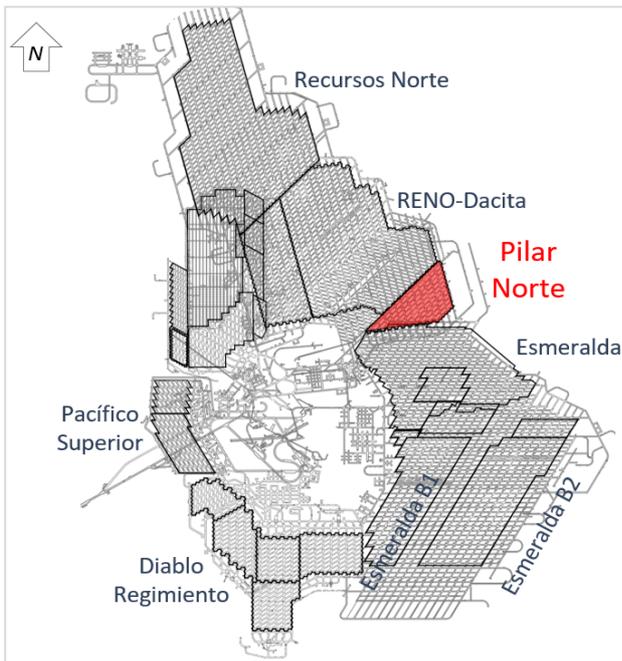


Figure 1 Mines in operation at El Teniente Division.

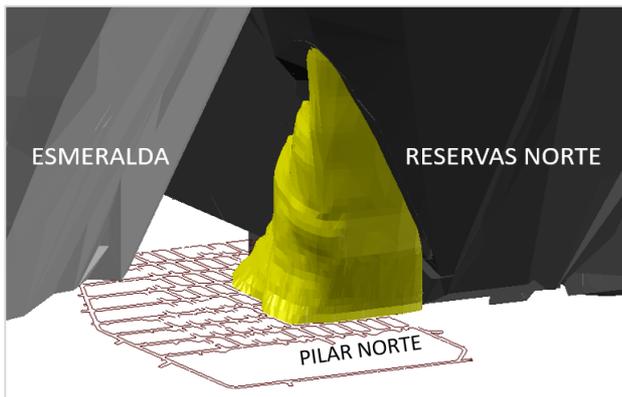


Figure 2 Geometric condition of cavities in Pilar Norte mine.

2 INSTRUMENTATION DESIGN

To carry out the instrumentation design, the following points were taken into consideration:

- The gradual growth of the Pilar Norte cavity towards Esmeralda must be monitored.
- The projection of incorporation of the Pilar Norte area and the sector where the connection of cavities is likely to materialize.
- The instrumentation will be carried out by inserting devices into perforations made from Esmeralda towards Pilar Norte.
- The perforations must be sub-horizontal to ensure the gradual collapse of instruments

and should reach the vicinity of the current Pilar Norte cavity (April 2021).

- The instrument must be selected to measure the collapse of rock blocks with a resolution of less than 5 meters.
- Ideally, the instrument should transmit its information wirelessly within the drill hole, eliminating the risk of cable cutting, and its autonomy should ensure a minimum monitoring period of 5 years.
- The monitoring of the instruments must be carried out remotely.

In Figure 3, a profile view of the caving monitoring instrumentation is presented, which includes the instrumentation of two drill holes performed from Esmeralda towards the Pilar Norte cavity.

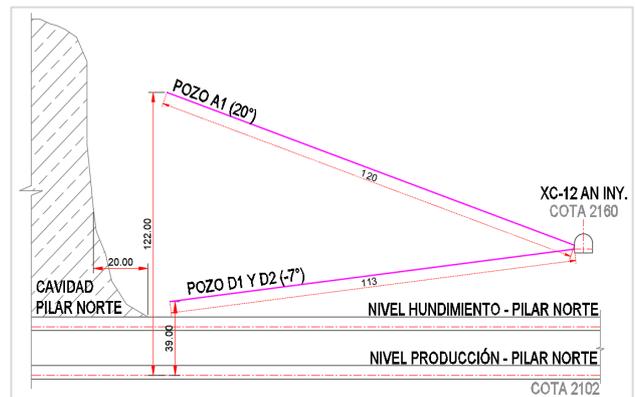


Figure 3 Instrumentation Design for Caving Monitoring, Pilar Norte Mine.



Figure 4 Instrument Installation Methodology

The inserted instruments are Smart Markers, known for wireless communication among

themselves. Regarding the installation, these instruments are placed every 2 meters, secured to a PVC conduit, along with coaxial cable (see Figure 4).

A total of 72 instruments were installed in the ascending drill hole, and 71 in the descending drill hole.

Regarding the data transmission system, wiring is done from the antenna located at the collar of each drill hole to the datalogger (approximately 300 meters). From the datalogger, and through optical fiber (approximately 740 meters), the connection to the internal network of the division is established. Subsequently, it becomes possible to send the data to the unit's server and display it on a dashboard.

3 DATA ANALYSIS

3.1 Change in Inclination of Devices

The data provided by the devices are obtained through the internal system of the El Teniente Division, which is remote and online. It was developed by the Geomechanical Instrumentation and Data Analysis Unit (IGAD). These data are stored as raw data and, in turn, processed according to their acquisition frequency.

The sampling frequency was initially set at 1 measurement every 24 hours. However, in accordance with the device's lifespan requirements for monitoring the evolution of the caving in the Pilar Norte Mine, it was changed to 1 measurement every 72 hours for all devices in both instrumented drill holes.

The devices provide information on inclination and orientation relative to magnetic north, along with the date and time of each measurement. To analyze the behavior of the devices, a baseline measurement was taken on April 5th, 2021 (following the installation of instruments and grouting), which is used as a reference for the periodic calculation of the relative variation in inclination and orientation with respect to magnetic north.

According to preliminary studies, it was determined that the analysis of device behavior

would be carried out through the variation in inclination and its derivatives.

Thus, Figure 5 and Figure 6 illustrate the cumulative absolute change in inclination of the devices in the descending drill hole (drill hole 1) and the ascending drill hole (drill hole 2), respectively.

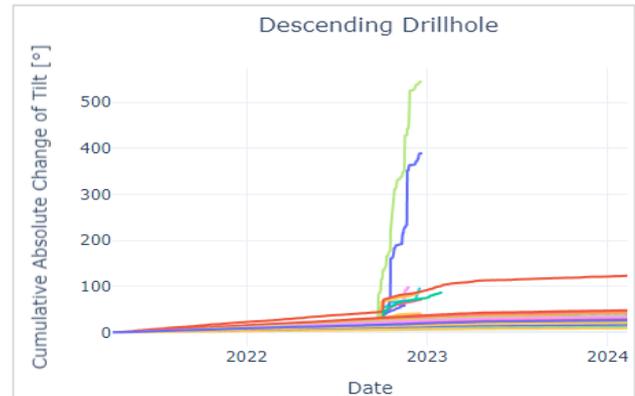


Figure 5 Accumulated change in inclination, descending drill hole.

Each color represents the behavior of each smart marker in the descending drillhole for a total of 71 units.

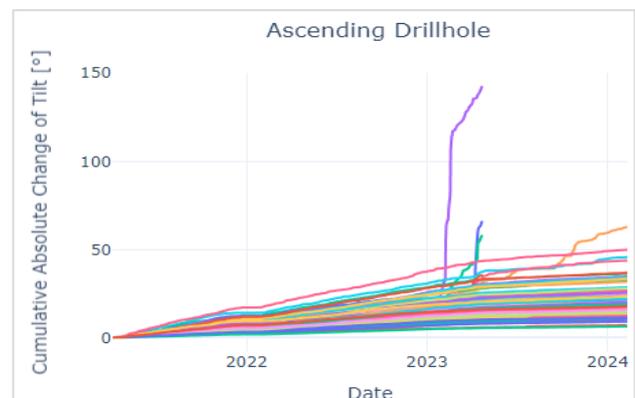


Figure 6 Accumulated change in inclination, ascending drill hole.

Each color represents the behavior of each smart marker in the ascending drillhole for a total of 72 units.

Additionally, considering that it is possible to monitor the connection status of the devices, where it is defined that a device disconnection occurs when it moves more than 5 meters away from the nearest device. This implies that the device collapsed with the rock block containing it.

3.2 Non-disconnected Devices

The devices that have not disconnected currently exhibit relatively constant rates of inclination change, as shown in Figure 7 and Figure 8 for the descending and ascending drill holes, respectively. There are slight variations in the rate of inclination change.

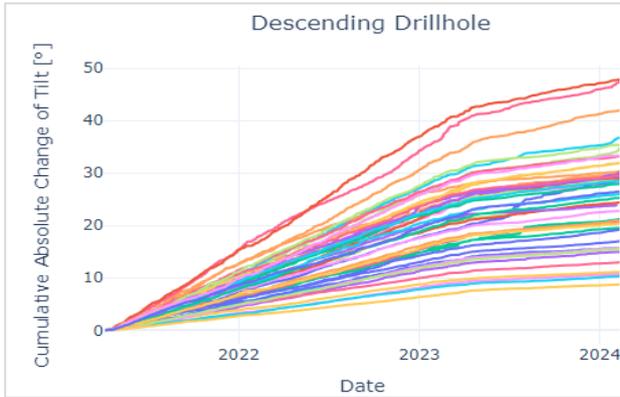


Figure 7 Accumulated change in inclination of non-disconnected devices, descending drill hole.

Each color represents the behavior of each smart marker in the descending drillhole for a total of 49 units.

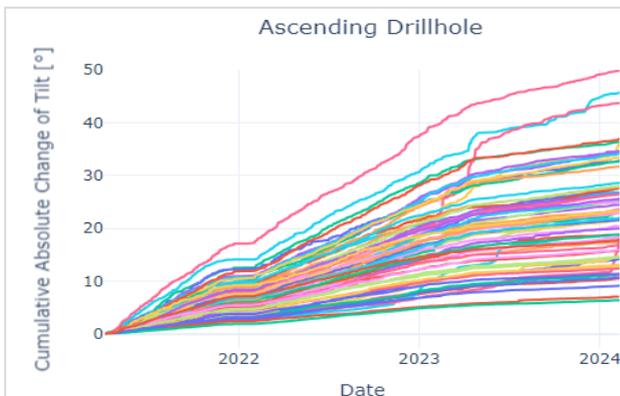


Figure 8 Accumulated change in inclination of non-disconnected devices, ascending drill hole.

Each color represents the behavior of each smart marker in the ascending drillhole for a total of 68 units.

3.3 Disconnected Devices

During the data analysis period of the installed devices, three temporal instances of instrument disconnection have occurred, characterized by the loss of groups of instruments (the

disconnection does not happen individually or sequentially). This indicates that the progress of the collapse covers a distance greater than two meters (the installation distance of the instruments).

Two of the disconnections occurred in the descending drill hole, and one in the ascending drill hole. In total, 26 devices have been disconnected from the system: 22 devices in the descending drill hole and 4 devices in the ascending drill hole. All of them correspond to devices located closer to the bottom of the drill hole and always occur in batches of devices.

The devices that are in the process of disconnecting mostly show an increase in the rate of inclination change. This increase in the rate of change is sustained for a period of time until the device finally disconnects.

Thus, two behaviors are observed prior to the disconnection of the devices:

- Disconnection without an increase in the rate of inclination change.
- Disconnection following a sustained increase in the rate of inclination change.

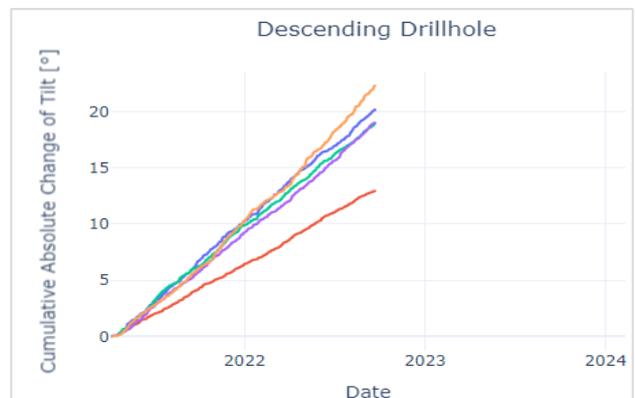


Figure 9 Accumulated change in inclination of disconnected devices without an increase in rate, descending drill hole.

3.3.1 Disconnection without an increase in the rate of inclination change.

This behavior occurred in the initial devices that experienced a disconnection from the system and it is specific to the 5 devices farthest from the collar of the descending drill hole. They did not exhibit a sudden increase in the rate of

inclination change, disconnecting abruptly, as shown in Figure 9.

Each color represents the behavior of each smart marker in the descending drillhole for a total of 5 units.

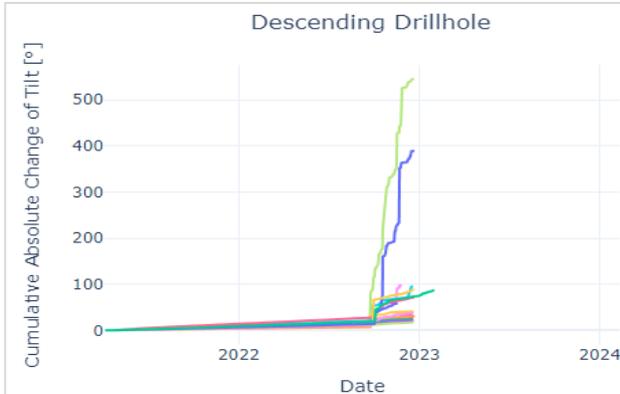


Figure 10 Accumulated change in inclination of disconnected devices with an increase in rate, descending drill hole.

before finally disconnecting from the system, as shown in Figure 10 and Figure 11.

Each color represents the behavior of each smart marker in the descending drillhole for a total of 17 units.

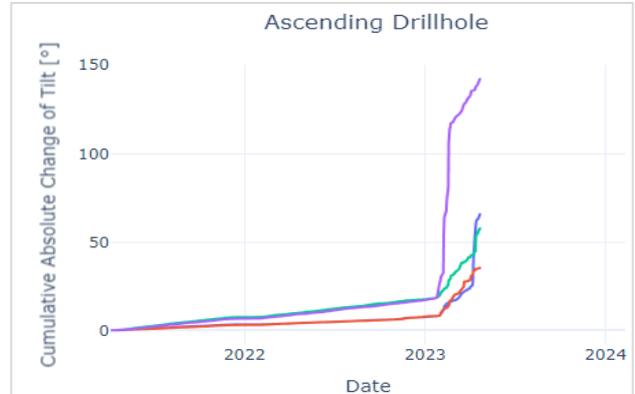


Figure 11 Accumulated change in inclination of disconnected devices with an increase in rate, ascending drill hole.

3.3.2 Disconnection following a sustained increase in the rate of inclination change.

This behavior was observed in devices disconnected in both the ascending and descending drill holes. It is characterized by a significant increase in the rate of inclination change compared to other devices, which persisted for a period of approximately 5 months

Each color represents the behavior of each smart marker in the ascending drillhole for a total of 5 units.

Thus, given the observed behaviors, it is possible to correlate a significant (more than 10 times the average) and sustained increase in the rate of inclination change with an imminent disconnection process of the device.

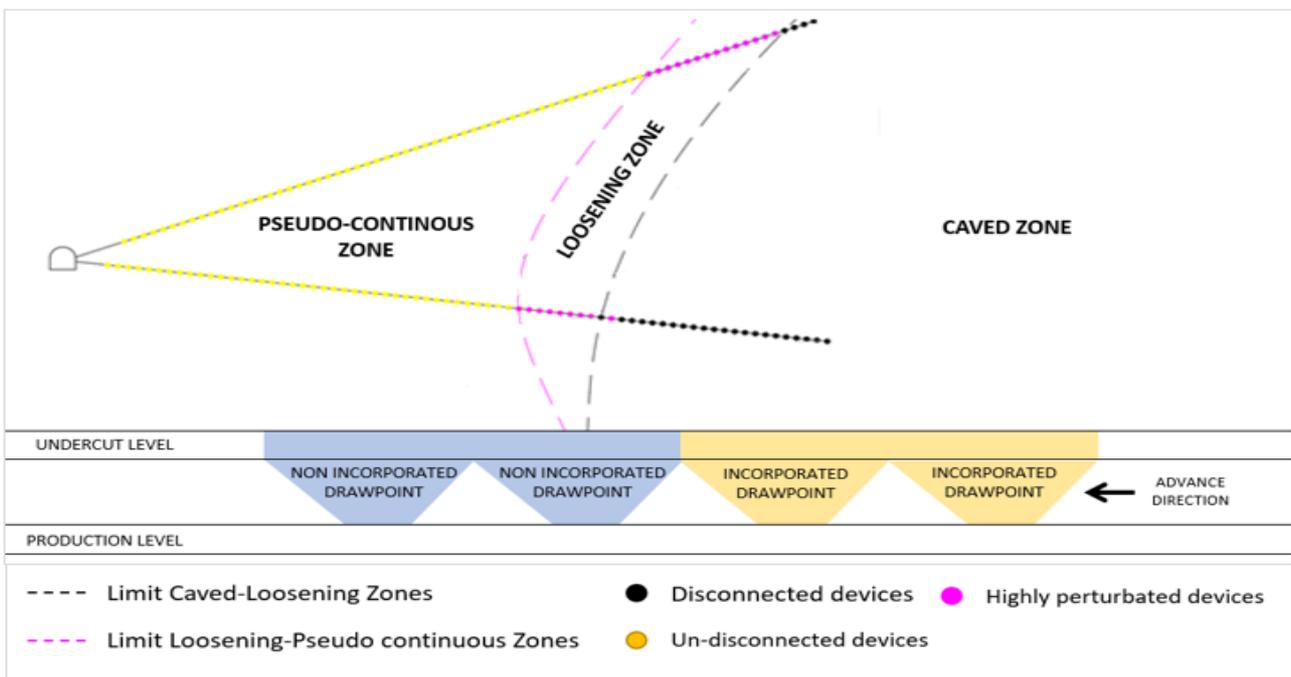


Figure 12 Conceptual model of caving and expected behavior of devices.

3.4 Relationship between Behavior and Conceptual Caving Model

Additionally, these behaviors correlate with three of the five zones described in the conceptual Caving model (Duplancic, 2001), as illustrated in Figure 12.

Thus, the zone in which a device is located is defined based on the following parameters:

- **Pseudo-Continuous Zone:** The devices exhibit a quasi-constant and low-magnitude rate of inclination change (rate of inclination changes less than 0.03 [°/day]), without abrupt variations in the accumulated inclination (changes less than 0.21 [°] in seven days). This likely results from the natural movement of the rock mass caused by various stress interactions in the area or due to instrument sensitivity (measurement error).
- **Loosening Zone:** The devices exhibit a sudden and significant increase in the rate of inclination change (greater than 0.5 [°/day]), which persists for the period during which the device is in this zone. This is associated with mining activity in the sector (rate of area incorporation and extraction).

Conceptually, the initial phase involves the creation of a seismogenic zone (activation and formation of fractures), which is not detectable by the devices due to the movements falling within the instrument's sensitivity range. Consequently, a fractured zone is formed, defining rock blocks. Coupled with the loss of confinement in the area, these blocks start to mobilize, resulting in an increase in the rate of movement recorded by the devices.

- **Caved Zone:** The devices disconnect from the system (move more than 5 meters away from the nearest device), caused by the displacement of the rock blocks containing the inserted devices (gravitational flow).

3.5 Analysis of Behavior in Relation to Mining Extraction and Incorporation in Pilar Norte Mine.

In general terms, since the instrumentation was carried out in Pilar Norte Mine, four periods of particular behavior have been registered in the instruments, characterized by the loss of some devices as well as the registration of significant changes in their readings.

The above can be directly related to mining activity in the sector, emphasizing the effect of the height extracted at extraction points and the incorporation of area (see Figure 13 and Figure 14).

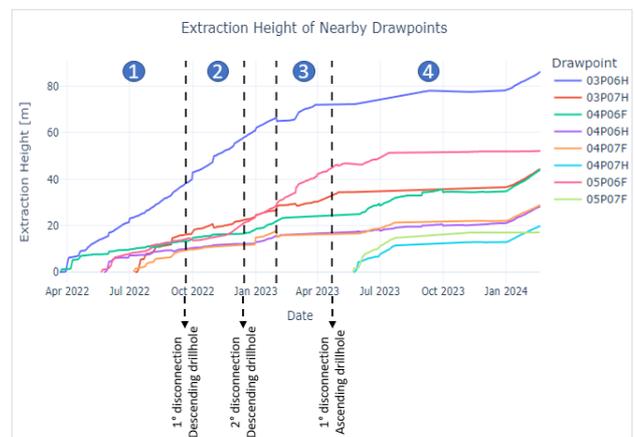


Figure 13 Height of extraction from draw points near instrumentation.

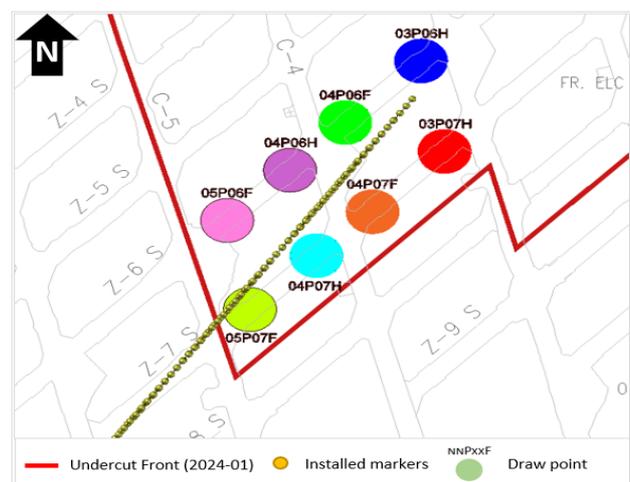


Figure 14 Location of incorporated draw points near instrumentation.

3.5.1 Period 1: Time window prior to the first disconnection of devices in the descending shaft (September 21th, 2022).

As observed in Figure 9, the devices experienced an abrupt disconnection over time. This behavior is attributed to the instantaneous propagation of caving, which occurred due to the incorporation of the necessary area to propagate subsidence (in accordance with the span defined in the geomechanical guidelines of the sector). Thus, at the time of the blasting on September 21th, 2022, the required instability of the rock mass was induced to propagate caving vertically, causing the rock mass to fall along with the devices (see Figure 15).

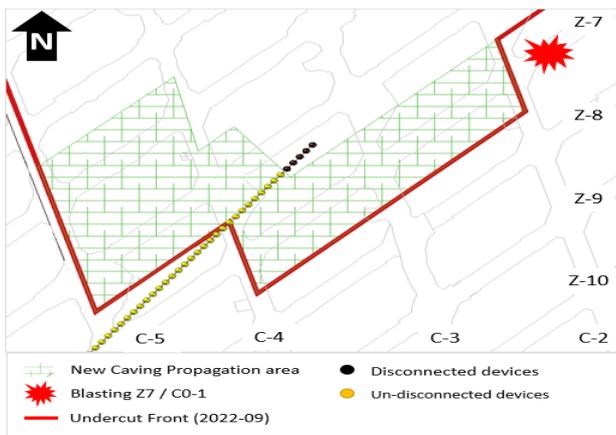


Figure 15 Incorporated area prior to the first disconnection.

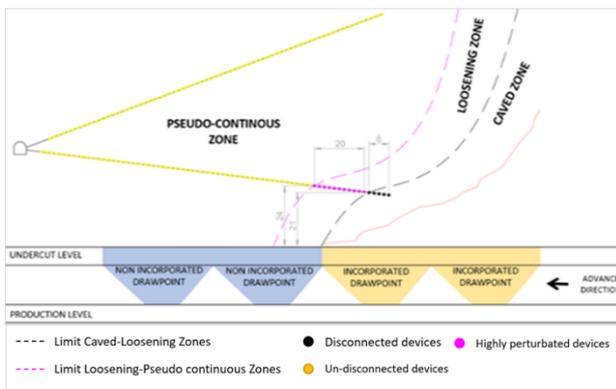


Figure 16 Conceptual model of the state of caving during the first disconnection in the descending drill hole.

According to the conceptual model developed earlier, this disconnection of devices from the descending drill hole implies an advance of caving during this period, as shown in Figure 16.

In terms of the height of the extracted column, the extraction of point 03P06H stands out, which theoretically should have exceeded the bottom of the descending well by at least 10 meters (prior to disconnection of the instruments). This point indicates that the extraction of the points was not causing subsidence propagation vertically, and possibly this extraction corresponds to dilution from the north.

3.5.2 Period 2: Time window prior to the second disconnection of devices in the descending drill hole (21-09-2022 – 31-01-2023).

As observed in Figure 16, during this period, a halo of disturbed devices was generated, which according to the conceptual model were in the loosening zone. This is related to the increase in the extracted height from nearby extraction points (see Figure 13 and Figure 14).

This behavior extended from the 6th device to the 24th device (36 meters of collapse), which disconnected completely on the day January 31st, 2023. The above confirms the system's capacity to measure the gradual growth of the cavity in the direction of the caving advance (see Figure 17).

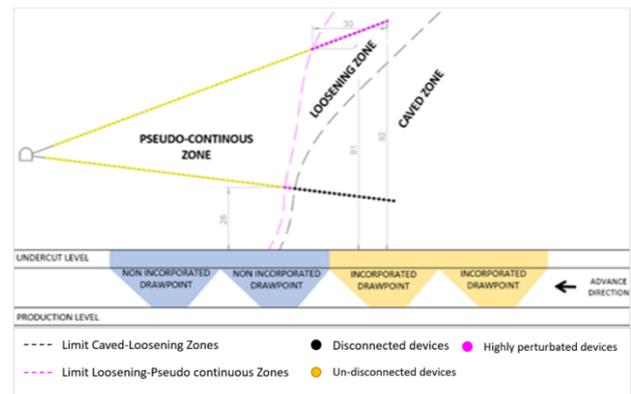


Figure 17 Conceptual model of the state of caving during the second disconnection in the descending drill hole.

3.5.3 Period 3: Time window prior to the first disconnection of devices in the ascending drill hole (from January 31st, 2023 until April 22nd, 2023).

During this period, the 5 devices located at the bottom of the ascending drill hole recorded an

increase in the rate of inclination change. This increase persisted from January 2023 until the first 5 devices disconnected in April 2023, maintaining high movement rates for the last device (nearest device). According to Figure 13, it is possible to observe that a high extraction rate persists at the nearest points.

Thus, similarly to the devices in the descending drill hole, the advancement of the subsidence front, extraction from nearby points, and the incorporation of new extraction points led to the progression of caving, this time at higher elevations, as seen in Figure 18.

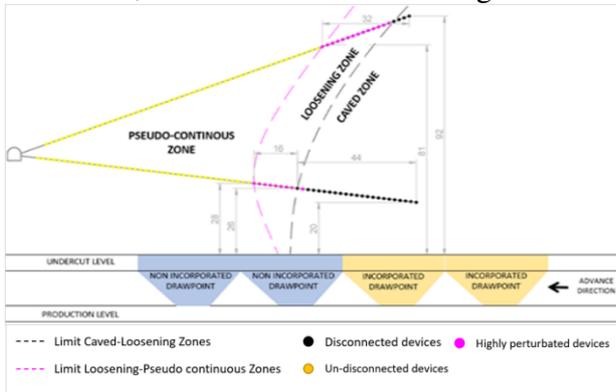


Figure 18 Conceptual model of the state of caving during the first disconnection in the ascending drill hole.

3.5.4 Period 4: Time after the collapse in the ascending drill hole (april 2023 - present).

This last period corresponds to the time between April 2023 and the present. During this period, low rates of inclination change are observed, except for the last connected device of each drill hole (the ones farthest from the collar currently). This is mainly due to the halt in the advancement of the caving front and the low extraction levels in the sector, as shown in Figure 13.

Currently, the advancement of the undercut front and extraction with normal production rates resumed in January 2024, which has not generated significant changes in the instruments of both drill holes.

3.6 Inclination Rate Change Thresholds

As described earlier, the study primarily focuses on the inclination rate changes of the devices. In

this regard, it was established that devices located in a loosening zone exhibit a sudden and abrupt increase in the rate of inclination change.

To establish the alert criteria, Figures 19 and 20 are presented, showing the ranges of observed variation rates in devices that remain connected.

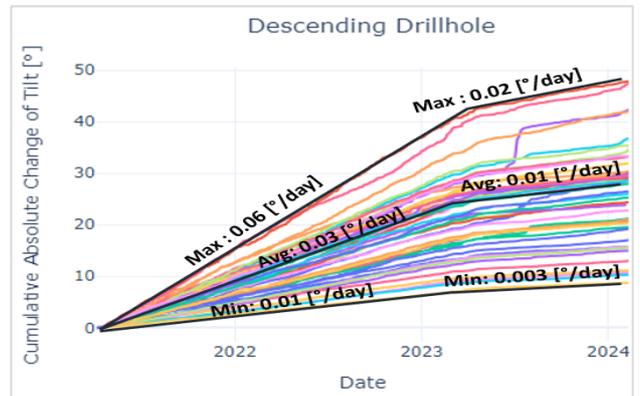


Figure 19 Thresholds for inclination rate change in undisturbed devices, descending drill hole.

Each color represents the behavior of each smart marker in the descending drillhole for a total of 49 units. While the black lines represent the maximum, minimum and average rate of daily dip change for non-disconnected markers.

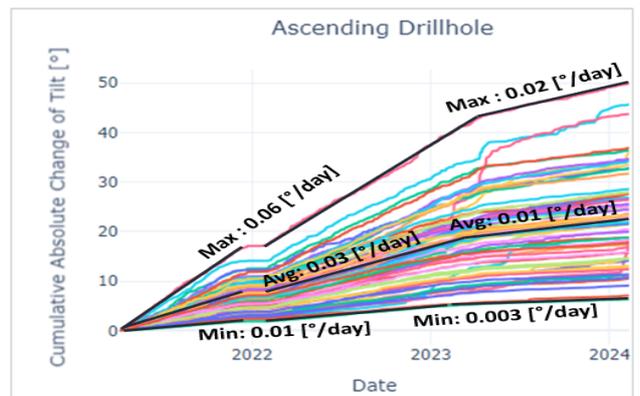


Figure 20 Thresholds for inclination rate change in undisturbed devices, ascending drill hole.

Each color represents the behavior of each smart marker in the ascending drillhole for a total of 68 units. While the black lines represent the maximum, minimum and average rate of daily dip change for non-disconnected markers.

It is observed that in both drill holes, the ranges of inclination rate change are similar. Additionally, in both drill holes, there is a break

in the slope, which occurs simultaneously with the propagation of subsidence in height when the devices in the ascending drill hole disconnect.

In this way, it was determined that devices not in the process of disconnection or in the loosening zone of the rock mass have inclination rate changes within these ranges [0.003 – 0.02] [°/day].

On the other hand, devices that are close to disconnection, meaning they are in the loosening zone and near collapse, exhibit inclination rate changes at least 10 times higher than the average inclination rate recorded in devices located in the pseudo-continuous zone.

4 REMOTE AND ONLINE MONITORING

As described earlier, the monitoring system collects information with a frequency of one measurement every 3 days. This data is stored within the servers of the El Teniente Division and is later processed and presented in a web system developed by the Geomechanical Instrumentation and Data Analysis Unit (IGAD).

The website updates information daily from the servers and provides graphs showing the status of devices (connected/disconnected), inclination changes, and orientation with respect to magnetic north for each installed device.

5 CONCLUSIONS

The implementation of monitoring instrumentation for Caving in Pilar Norte Mine has provided valuable information on the evolution of the cavity, enhancing our understanding of the relationship between mining activity and the propagation of caving.

The use of Smart Markers, strategically installed, allows wireless communication and reliable data collection. This instrumentation allowed for an analysis of the geometry of the caving and its response to extraction activities.

The retrospective analysis of disconnected devices allowed the establishment of movement speed thresholds, enabling the identification of areas prone to collapse before it occurs.

The correlation between mining activity and disturbances in the instrumented drill holes highlighted the dynamic interaction between the extraction process and the geometry of the cavity. This technical analysis, supported by two years of data collection, contributes to continuous improvements in operational strategies.

The establishment of thresholds for the inclination rate change proves effective in identifying devices in the process of disconnection. This information serves as an early warning system, enabling timely interventions and preventive measures to ensure the safety of mining operations.

The continuous data monitoring system developed by the Geomechanical Instrumentation and Data Analysis Unit (IGAD) provides real-time information on the status of devices and changes in their readings. This accessibility enhances decision-making processes and contributes to the overall safety and efficiency of mining operations.

Moreover, the volume of stored data is valuable for feeding and calibrating numerical models, by the explicit incorporation of the cavity geometry measured by the instruments into the models. Reducing the error associated to the measure of stresses in the mine.

In conclusion, and in accordance with the findings presented in this study, the ability to monitor the evolution of Caving and its relationship with mining activity in the sector is confirmed. This case of study establishes a standard for Caving monitoring at División El Teniente, allowing for the implementation of sustainable and efficient mining practices that balance production goals with a focus on safety.

This case study corresponds to a first review, covering an analysis period of approximately 3 years. Pilar Norte is still in the process of incorporating the area, and at least an additional 3 years of monitoring are projected.

REFERENCES

- Duplancic, P. (2001). Characterization of caving mechanisms through analysis of stress and seismicity. PhD thesis, University of Western Australia.