Caving 2022 - Y Potvin (ed.)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-3-4
doi:10.36487/ACG_repo/2205_73

Back-analysis of gravitational flow MB N01-S01 at Chuquicamata underground mine

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Abstract

Chuquicamata underground mine (MCHS) is currently extracting ore from the first level through macroblocks arranged from North to South. This work analyses the efficiency of the design of drawpoint spacing in terms of gravity flow for macroblocks (MB) N01-S01, with a drawpoint spacing of 16 × 16 m^2. The characterisation of gravity flow, in terms of reserve recovery, remaining ore, height of the interaction zone (HIZ) and quantification of fines extracted was performed using numerical simulations in FlowSim BC v6.1 based on the grade of copper extracted and the movement of cave trackers at MB N01-S01 from May 2019 to February 2021.

Isolated and interactive draw flow were compared in FlowSim BC v6.1. Isolated draw considers that the maximum diameter of an isolated ellipsoid is 12 m, which causes isolated flow given the spacing between drawpoints. Interactive draw considers that the diameters of ellipsoids are greater for coarse fragmentation. In the case of the macroblocks N01-S01, extraction ellipsoids diameter were obtained that evolve up to 34 m at 150,000 tons extracted per drawpoint.

Results showed that when isolated draw was used an error of 9.7% was obtained in the copper grade compared with the measured grade, while with interactive draw a 1.3% error was obtained. Both flow models were compared in terms of the movement of markers using 159 cave trackers installed in the western sector of the MB N01-S01. Horizontal movement during flow with interactive draw was found to be more representative of the actual displacement with an error of 2.6% in terms of the horizontal average. In contrast, the displacement obtained by isolated draw showed an error of 66% with respect to the actual records.

In addition, an analysis of the expected loads induced on the apex pillar at the production level was carried out under three extraction conditions: 5 kton, 10 kton and 40 kton extracted. In the first condition, no flow interaction was observed on the main pillar and therefore all the material exerted load with an induced stress of 1.15 MPa. In the 10 kton condition, interaction was observed, and the estimated induced stress was 1.23 MPa. Finally, at the 40 kton level of extraction, a larger broken column on the pillar was noted with the induced stress estimated at 3.92 MPa.

From the flow analysis of MB N01-S01, it is concluded that:

- *With the evidence obtained in terms of the results of grades and cave trackers, interactive and not isolated draw occurs in the N01-S01 macroblocks.*
- *The height of interaction of the flow is defined by the ellipsoids of movement which evolve with extraction. For the 16 × 16 m^2 layout with a dominant fragmentation d80 = 1.1 m, ellipsoid diameters of up to 34 m are expected at the 150 kton extracted, while at 50 kton extracted the ellipsoid diameter is estimated to be 26 m with HIZ between 20 and 25 m.*

Keywords: *Chuquicamata, gravity flow, cave trackers, load-induced*

1 Introduction

The Chuquicamata Underground Mine (MCHS) is located 15 km north of Calama, Chile and operated by Codelco. The mine transitioned from a century-old open pit operation to an underground mine using the macroblock caving method to extract deep reserves. This transition should prolong the life of the mine for at least 50 years. Moreover, block caving has been shown to represent the best alternative for a massive and low-grade mineralised orebody, as it generates higher production with lower operating costs as compared to other underground methods (Araneda 2015).

The MCHS is extracting ore from the first level at 1,841 masl (metres above sea level) using macroblocks (MB) located from North to South. One of the challenges in level design is that both the rock quality and the geometry of the orebody are not homogeneous on the N-S axis. This study analyses the efficiency of the extraction level design in terms of gravity flow through back-analysis of the MCHS MB N01-S01. The analysis includes recovery of reserves, height of the interaction zone (HIZ), and the amount of fine copper remnant for the current extraction level design – 16 × 16 m^2 drawpoint spacing and includes a comparison of loads induced on the apex pillar at the production level under three extraction conditions.

2 Methodology

Figure 1 presents a scheme of the stages carried out in this study, which consists of a flow analysis and quantification of extractable reserves for the different macroblocks using FlowSim BC v6.1.

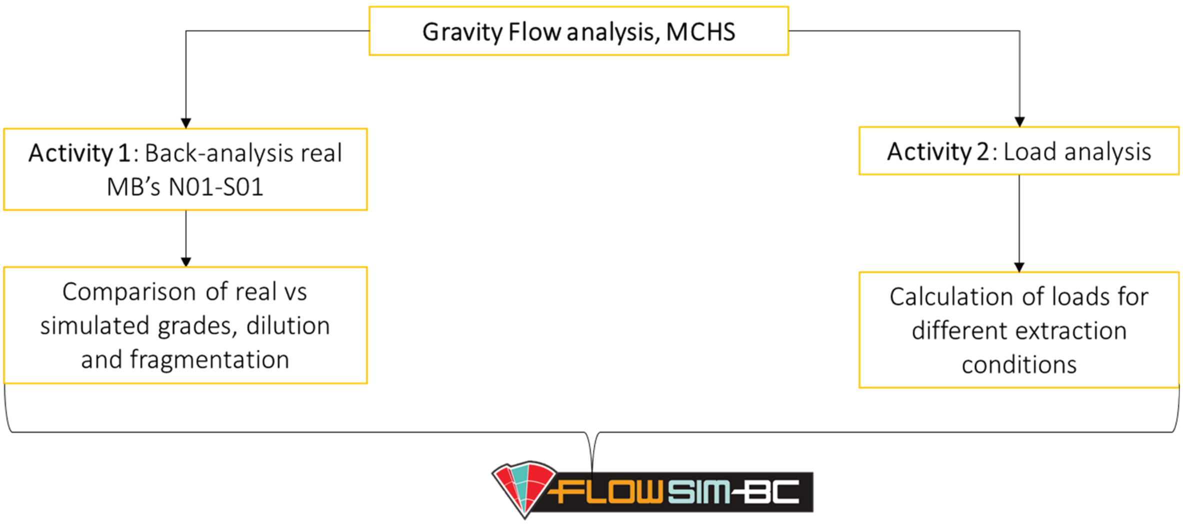

Figure 1 Scheme with the project methodology

In the first stage, a back-analysis of the extraction from May 2019 to February 2021 of MB N01-S01 was carried out. At this stage, the results of the simulation were compared with the extracted grades and the movement of cave trackers installed in the central MBs.

In the second stage, the induced stresses on the pillar due to the mass of broken ore were estimated for three extraction conditions.

3 Sector analysed

Table 1 summarises the main design characteristics of the production level for MB N01-S01.

Table 1 Summary of production level design

Parameters	MB N01-S01
Design	Layout 16 × 16 m^2
Drawpoint number	294
Footprint area (m^2)*	75,264
Extraction drives	8
Extraction drifts	26

(*) The m^2 of the footprints were estimated as the area of each drawpoint multiplied by the number of drawpoints in the production level.

Figure 2 shows a plan view with the production level design of MB N01-S01.

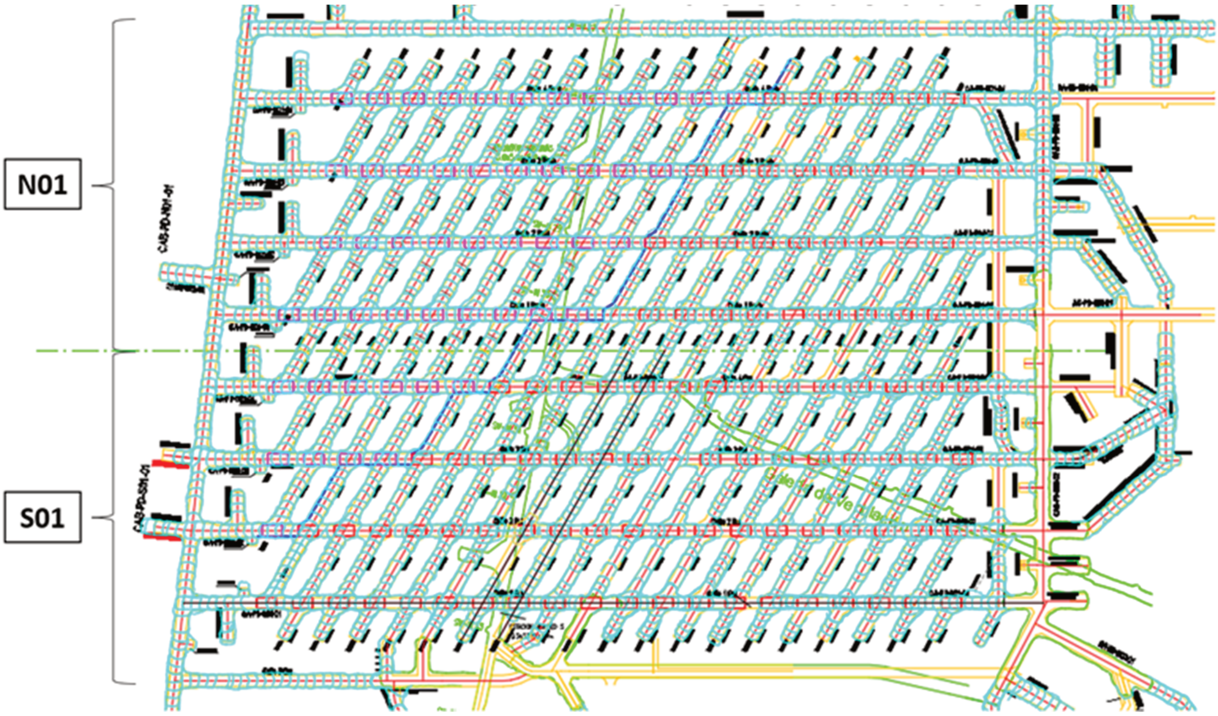

Figure 2 Design of the production level macroblock N01-S01 layout 16 × 16 m^2

4 Gravity flow analysis of MB N01-S01

In the first stage, the results of a flow simulation were compared to extracted grades and movement of cave trackers installed during actual extraction from May 2019 to February 2021.

Simulations were performed in FlowSim BC v6.1 considering two gravity flow theories:

- For flow Condition A, Isolated Draw, Laubscher's (1994) abacus was used in which the fragment size of the central MB is in the range of 0.1 to 2 m. If a drawpoint width of 4 m is taken into account, the maximum ellipsoid diameter is 9 m in isolated draw (12 m interactive), which translates into a maximum spacing between drawpoints of 15 m.
- Flow Condition B, Interactive draw, is the flow theory contained in FlowSim and has been widely calibrated and validated through laboratory-scale experiments as well as in mining operations. This second theory has allowed the rules of design to be challenged, observing that the diameters of

ellipsoids are larger (Figure 3), in special to a coarse fragmentation (d80 = 1.1 m of the QIS rock in MB N01-S01). FlowSim considers mechanisms such as:

- Preferential flow controlled by dominant structures.
- Inclusion of cave back and/or break angles.
- Fines migration (Castro et al. 2022).
- Secondary fragmentation in the new version of FlowSim BC v6.3.

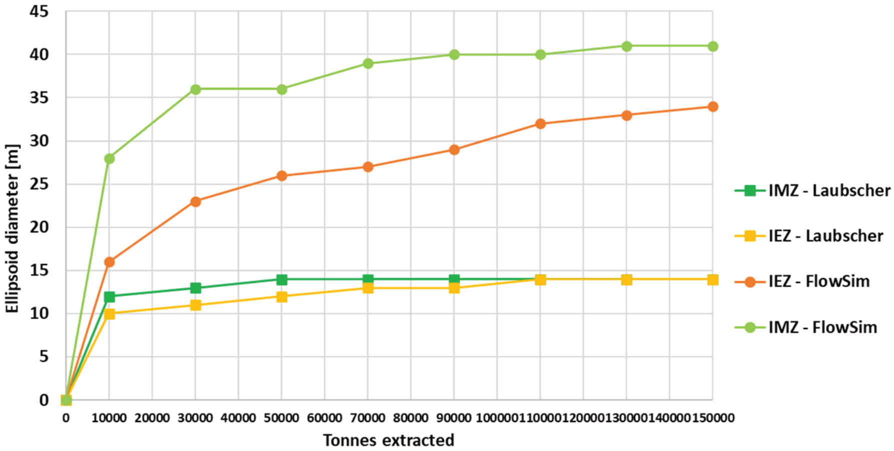

Figure 3 Evolution of isolated extraction zones (IEZ) and Isolated movement Zones (IMZ) as a function of extraction, considering flow condition A (Laubscher) and B (FlowSim). Modified from Le-Feaux et al. (2021)

Figure 4 shows the result of the FlowSim simulation of an isolated drawpoint considering both flow conditions. It is observed that the ellipsoid diameters obtained by Condition B are greater than expected using Condition A, reaching 34 m and 14 m respectively in terms of the isolated extraction zone (IEZ).

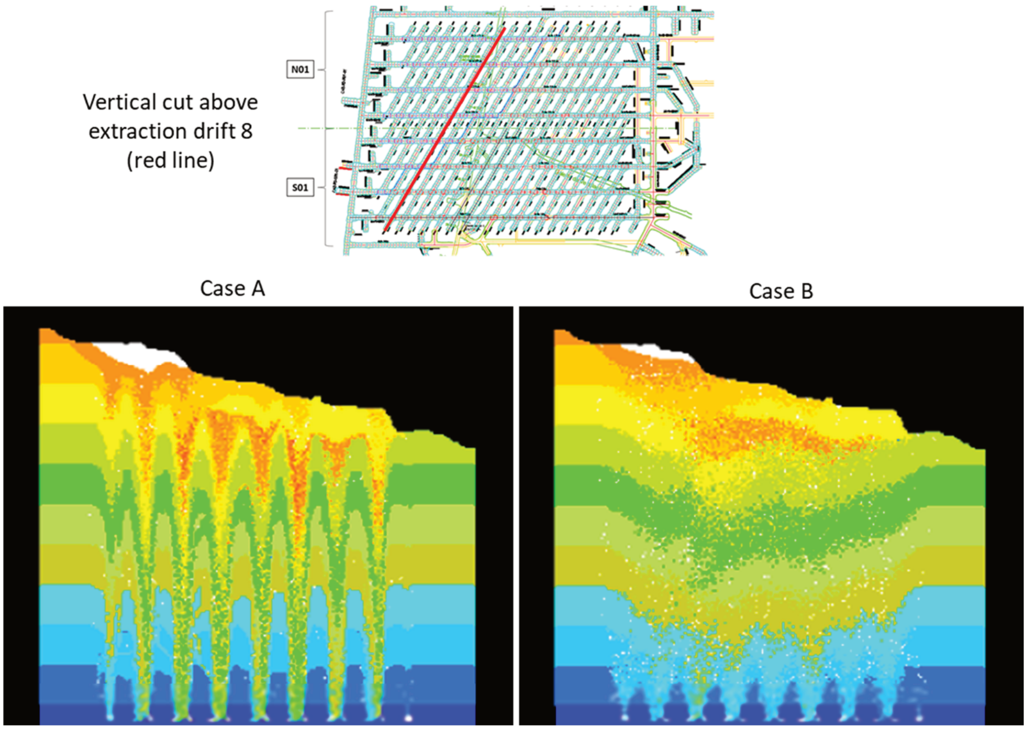

Figure 4 Vertical view over extraction drift 8 of the block model bands at the end of the actual extraction (February 2021). On the left the result is observed considering the diameter of ellipsoids according to Case A. The result of Case B is on the right

The actual extraction of MB N01-S01 was then simulated using the extraction diameter estimated with both flow conditions. Figure 4 shows a vertical view over extraction drift 8 of the central macroblock. It shows the dimensions of the block model in the last extraction period (February 2021). As can be seen, the ellipsoids according to flow Condition B interact (interactive draw), while the ellipsoids given by Condition A are narrow and do not overlap (isolated draw).

Figure 5 shows the trend of the extracted grades for flow Condition A and B compared to the actual grades.

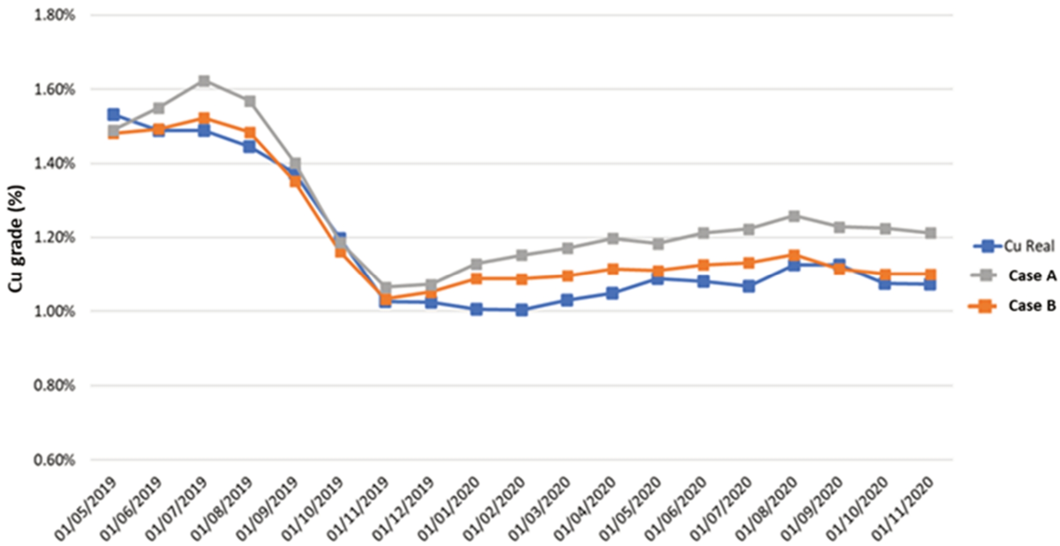

Figure 5 Comparison of real and simulated grades (FlowSim versus Laubscher)

Table 2 summarises the comparison of both flow models. With Laubscher, we obtained a 9.7% error in grades while with FlowSim an error of 1.3% was obtained in terms of grades.

Table 2 Summary comparison flow model for condition A and B

Macroblocks N01-S01	Actual	Condition A	Error	Condition B	Error
Fine Copper extracted (ton)	90,792	95,511	5.2%	88,261	-2.8%
Average grade	1.11%	1.22%	9.7%	1.13%	1.3%

Subsequently, the displacement of 159 cave trackers installed in the western sector of the central MB was compared in detail. Cave trackers are a system consisting of a series of wireless sensors which are installed in the rock mass and deliver information about their position while moving in the fragmented rock. The information is recorded once a day and the processing of information takes 48 hours. This system helps to understand the flow of material within the cave and its propagation. From the simulations in FlowSim BC v6.1, the displacement of the tracers obtained in both flow conditions was analysed and compared with the actual displacement recorded in MB N01-S01.

Table 3 summarises the basic statistics of horizontal and vertical movements for measurements and simulations respectively. It was observed that in terms of horizontal movement flow Condition B (FlowSim) was more representative of what happens in the field (actual), with an error of 2.6% in terms of horizontal average displacement. While the displacement obtained by Condition A (Laubscher) showed an error of 66% in comparison with the actual records.

Table 3 Summary of cave trackers displacement comparison

Displacement	Statistics	Actual	Condition A	Condition B
Horizontal	Minimum (m)	0	0.06	0.1
	Average (m)	7.7	2.6	7.9
	Maximum (m)	58.2	20.6	33.7
Vertical	Minimum (m)	0	0.3	0.9
	Average (m)	28.2	12.1	36.3
	Maximum (m)	110.8	91.5	111.8

To complement the analysis, the displacement of all the cave trackers installed over the extraction drive was analysed in detail because this area contains the greatest spacing between adjacent drawpoints and therefore the greatest risk of isolated draw. This analysis was carried out to check if movement occurred in this area and, therefore, interaction of the IMZ. For this analysis, a total of 36 cave trackers initially installed over the extraction drive were identified as indicated in Figure 6.

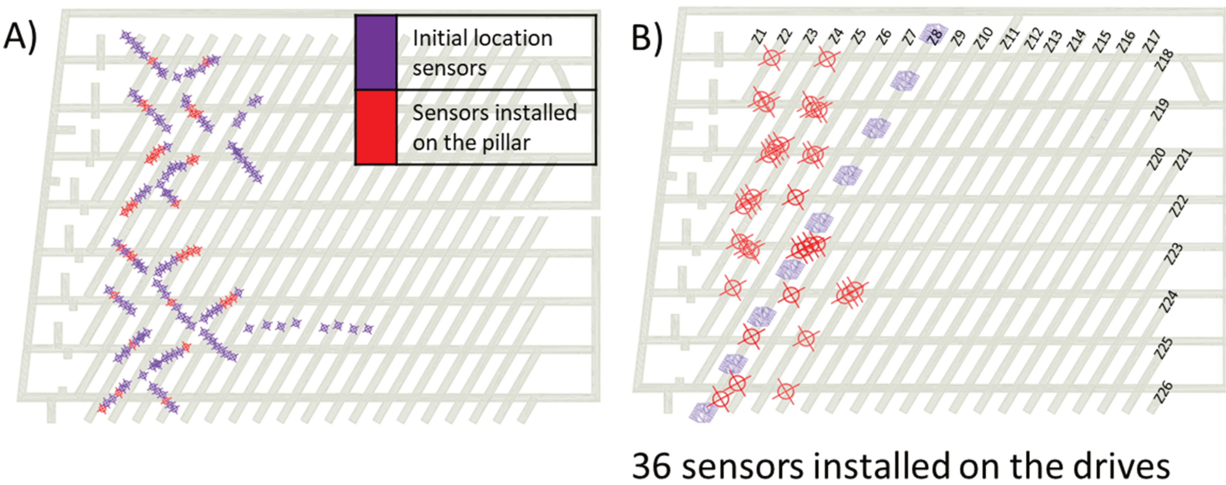

Figure 6 (a) Initial position of cave trackers installed, identifying those that are on the pillar; (b) Filter of cave trackers installed over the pillar

In Figure 7, a vertical view is presented in which the displacements of the cave trackers were compared. It shows that the final vector obtained by flow Condition B was more representative of what was recorded in the field as compared to Condition A.

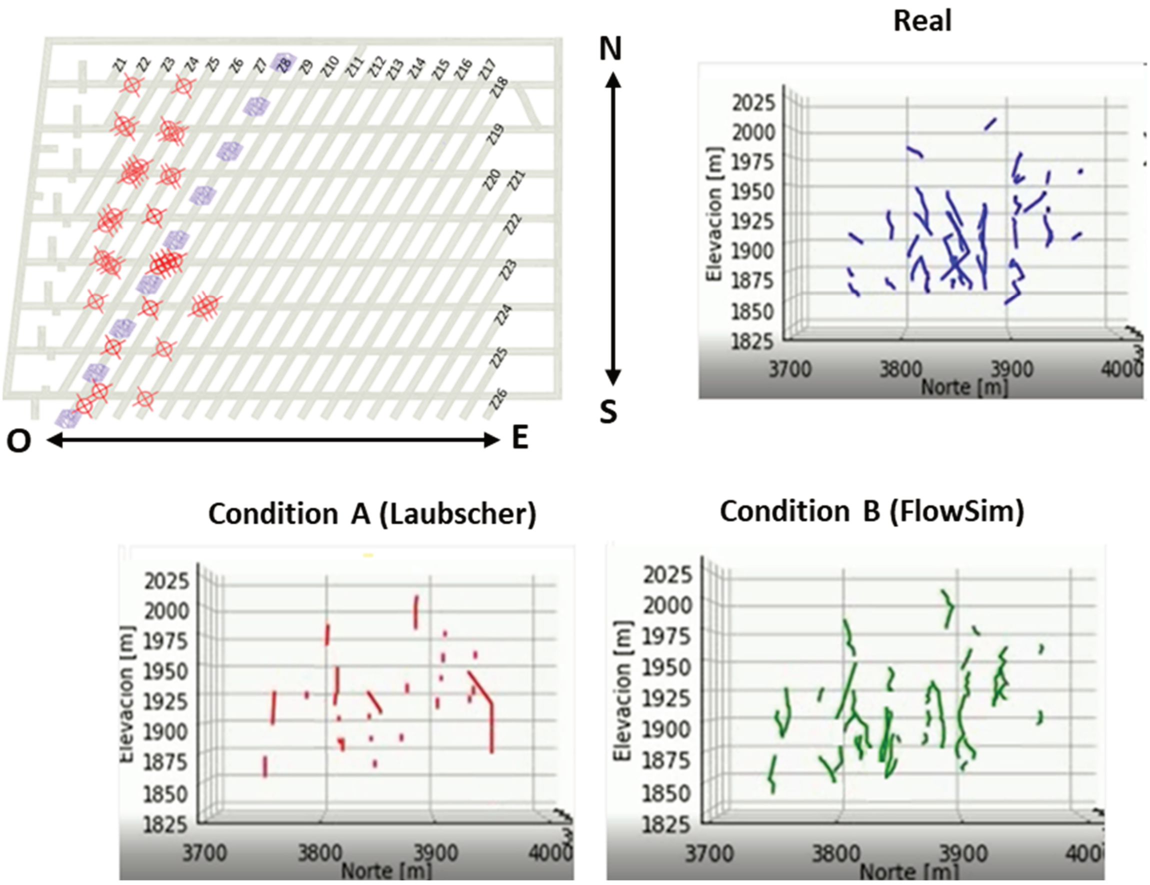

Figure 7 **Vertical view parallel to the extraction drift 8, where the actual displacements are compared with those simulated using both flow conditions**

When the displacement statistics of the cave trackers located over the extraction drives were assessed, the following were observed:

- There was movement of the cave trackers located over the pillar, with an average of 24 m of total displacement.
- The magnitude of the displacements obtained using flow Condition B was greater than those obtained according to flow Condition A. Table 4 summarises the actual and simulated average displacements with both flow theories.

Table 4 **Comparison of the average displacements of cave trackers installed over the extraction drives**

Average	Vertical displacement (m)	Horizontal displacement (m)	Total displacement (m)
Real	21.0	9.6	24.0
Condition A	10.6	2.7	11.3
Condition B	27.5	7.2	29.7

Figure 8 shows the distribution of total displacements. Seventy eight percent (78%) of the cave trackers moved less than 10 m using flow Condition A. However, 80% of the cave trackers registered in the field and 58% of the cave trackers simulated with Condition B achieved a total displacement between 10 m and 40 m.

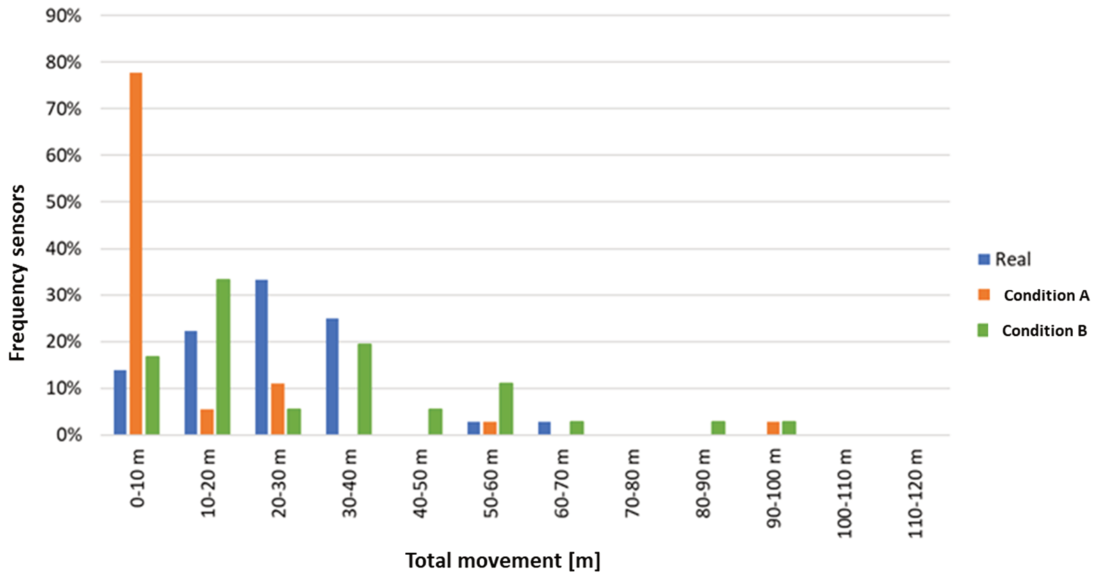

Figure 8 Distribution of the total displacements of cave trackers

With the evidence obtained in terms of the results of grades and cave trackers, interactive rather than isolated draw is observed and best represented in the simulation with flow Condition B.

5 Load analysis

The gravitational flow generates induced stresses on the pillars which could cause instability on the extraction level resulting in production delays; therefore, it is important to estimate what loads are presented for different extraction conditions. In this study, a hypothesis with two conditions was established for the estimation of these loads (Figure 9). In Condition 1 (Figure 9a) with 5 ktons extracted per drawpoint (uniformly), no interaction on the main pillar is observed and, therefore, all the broken material up to the cave back exerts loads on the production level. In Condition 2 (Figure 9b) there is an overlap of the ellipsoids of movement, and in this condition the pillar is being loaded by the muck pile without movement on the pillar with a height of 20 m (HIZ), and also by a percentage of the remaining column of broken ore to the cave back. This percentage corresponds to 40% of the loads in a situation of non-flow (Castro et al. 2020).

Given the above, three extraction conditions were analysed: 5 ktons, 10 ktons and 40 ktons extracted illustrated (Figure 9). Other important considerations for this analysis are summarised below:

- A uniform extraction per drawpoint is assumed.
- For the analysis it was assumed that in the flow zones there is no load; rather the load is transmitted to the area without flow.
- When there is no interaction, the exposed load is considered as the stress on the area without interaction, distributed in the exposed area of the pillar (marked in Figure 9 as the red line on the pillar).
- The load exerted by the broken ore on the pillar (blue triangle) is equal to 0.4 times the load in a situation of non-flow. Based on experiments, it has been observed that when the broken mineral is extracted it lowers the load to 40% of the initial value (Castro et al. 2020).
- The loads on the pillars were estimated using the following assumptions:
  - Broken mineral density = 2,000 kg/m^3.
  - The ratio of induced stresses due to flow is equal to $\sigma_v/\sigma_{v0} = 2$ (Castro et al. 2020). Where σ_v is sigma vertical or vertical stress and σ_{v0} is the induced vertical stress.

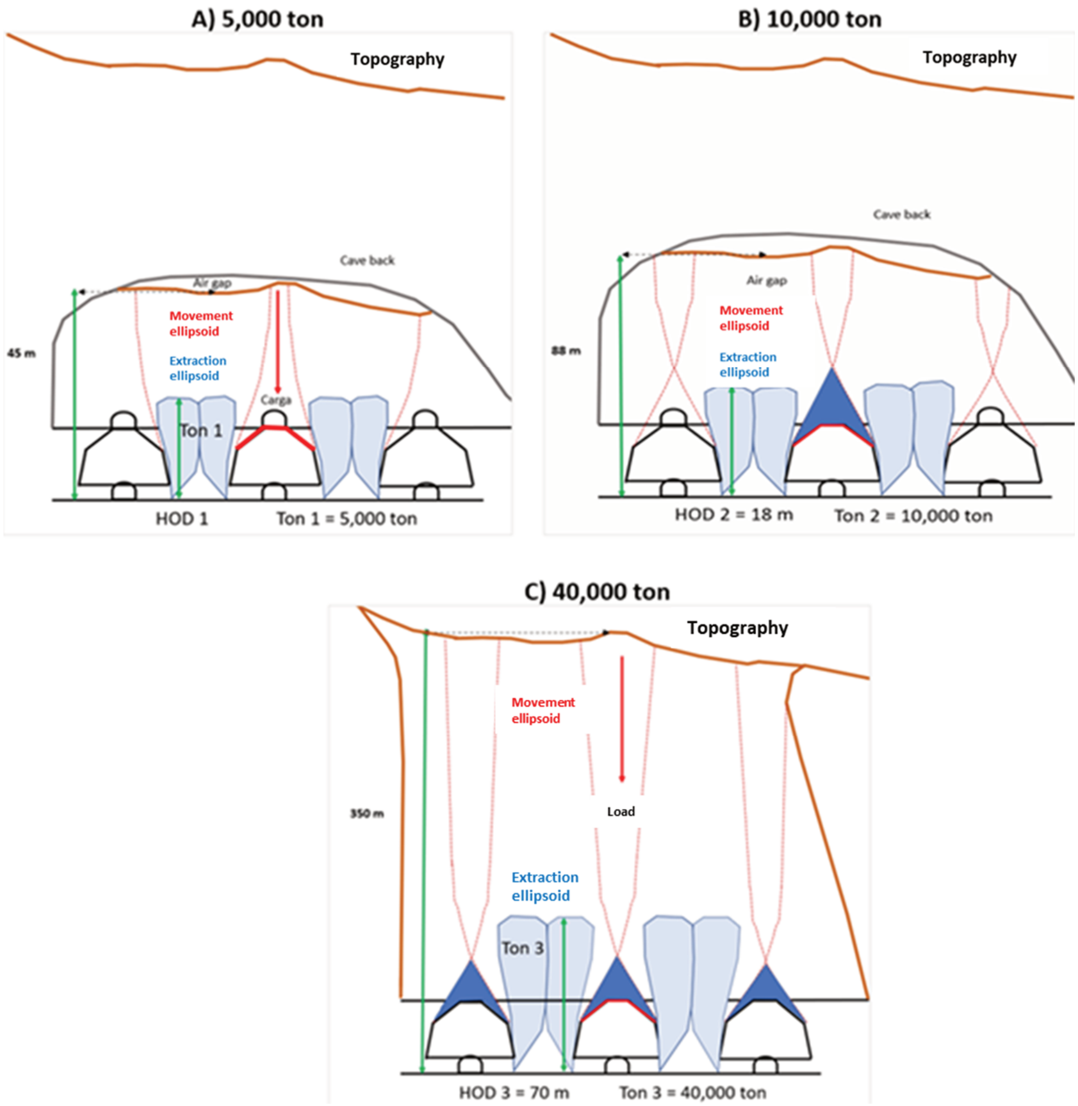

Figure 9 Diagram with the evolution of the cave back and flow ellipsoids for three extraction conditions, 5 kton, 10 kton and 40 kton extracted

In the first condition (5 kton extracted) there was still no flow interaction on the main pillar and therefore all the material exerts load, having an induced stress of 1.15 MPa. In the condition of 10 kton extracted there is already interaction, and the estimated induced stress is 1.23 MPa. Finally at the 40 kton level of extraction there is a larger broken column on the pillar where the induced stress is estimated at 3.92 MPa.

These loads were added, in a separate study, into a numerical model to further investigate if induced vertical loads due to flow could cause further deformation of the production pillars. The results indicated that only small extra deformations were added, in comparison to these due to the caving establishment so extra instability due to flow conditions were not expected to be relevant.

6 Conclusion

From the flow analysis of MB N01-S01 it was concluded that:

- With the evidence obtained in terms of the results of grades and cave trackers, interactive and not isolated draw occurred in the macroblocks studied.
- The height of interaction of the flow was defined by the IEZ ellipsoids which evolve with extraction. For the 16 × 16 m^2 layout with a dominant fragmentation d80 = 1.1 m of the QIS rock, ellipsoid

diameters of 34 m are expected at the 150 kton extracted and interaction heights between 20 and 25 m, with an average of 23 m.

The analysis of loads exerted on the pillars at the production level suggested the following:

- The load exerted on the pillar depends on the flow condition, i.e. whether there is interactive or isolated flow.
- The induced stress increases with increased extraction due to the greater load exerted by the broken ore.

Acknowledgement

The authors would like to thank the following professionals that actively participated in the study: Diego Guzman and Pablo Cid.

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