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Impact of undercut geometry on caving propagation

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ABSTRACT

Undercutting corresponds to the stage that begins the caving of the orebody, which consists of the basal cut of the ore column and the blasted material removal until the necessary air gap is achieved. One of the key factors for the success of this process is the design of the undercut geometry. The successful implementation of the undercut process requires careful management of various factors that ensure adequate caving propagation and an adequate ore flow to the drawpoints. This document presents an evaluation and analysis in terms of gravity flow using FlowSim BC®, analyzing the impact of undercut height, fragmentation, spacing between drawpoints and distance between production and undercut levels on the tonnage required to achieve the necessary air gap to ensure the caving propagation. From the simulation results, it was possible to determine the geometry of the blasted pile material and the tonnage necessary to reach the target air gap, where it is observed that a greater tonnage is required to be extracted to achieve the target air gap at a larger primary fragmentation size, greater spacing between extraction points, shorter distance between production and undercut levels, and greater undercut height. Finally, a sensitivity analysis was carried out in terms of bucket number and percentage of swell tonnage extracted until the target air gap was achieved. As a result, it is observed that a layout with greater spacing and a greater distance between levels requires greater swell tonnage removal of the undercut mineral to reach the air gap.

1 INTRODUCTION

In underground block or panel caving operations, caving begins by destabilizing and extracting the mineral at the base of the orebody, in a process called Undercut. As the blasted ore is extracted through the drawpoints, a void is generated collapsing the in-situ rock initiating the vertical propagation. The horizontal propagation of caving occurs as more drawpoints are incorporated under the undercut area (Brown, 2007).

Undercutting, therefore, plays a fundamental role in block/panel caving operations. Butcher (2000) suggests that the three main objectives of undercutting are:

- Generate a sufficient dimensions excavation to allow the beginning of caving.
- Achieve the required dimensions of the undercut area to initiate caving with minimal damage to the nearby rock mass.
- Reach as quickly as possible the hydraulic radius required to generate the caving, propagate it and consequently reduce the stress concentration produced by this operation.

Poor planning, design or implementation of undercut can risk the success, productivity and final costs of an operation. Among the main risks associated with the undercutting process are:

- Excessive concentration of stress (abutment stress) on the pillars and infrastructure of the extraction level (EL), which could cause delays in production and incur excessive costs due to the requirement for repairs and/or reconstruction and reinforcement.

- Coarse fragmentation, due to poor drilling and blasting design, which causes the presence of hang-ups and the need for secondary blasting at the drawpoints, thereby affecting the productivity.

In conjunction with undercutting, one of the variables that define the success of block/panel caving operations is the propagation of the cave back. During this stage, the extraction plans are tested with challenges associated with maintaining and managing operational safety, controlling seismicity, airblast risks and rock bursts (Guzmán, 2018).

Currently, one of the most accepted conceptual models to describe the mechanical behavior of caving has been proposed by Duplancic and Brady (1999). This model includes 5 regions, caved zone, air gap, zone of loosening, seismogenic zone and pseudo-continuous domain. The air gap zone corresponds to a volume of air defined between the cave back and the pile of caved material. The existence of an air gap will depend on the extraction and caving propagation rate.

Considering all these aspects, a successful implementation of the undercutting and breaking process requires careful management of the following factors (Brown, 2007):

- The undercut sequence and drifts development at extractions levels (EL).
- The geometry of the undercut front.
- The relative positions of, and distances between the undercutting front, the front of extraction level development and the extraction front.
- The rate of undercut advance, expressed in terms of the undercut area per unit of time.
- The height of the undercut.
- The shape of the undercut in the vertical section.

This study focuses on the impact of the last two factors, the undercut height and geometry, and their impact on the caving initiation process from a gravity flow point of view.

2 METHODOLOGY

In order to determine the role of undercut height in the caving process from a gravity flow point of view, the following stages are considered (see Figure 1):

1. Geometric undercut analysis, calculating the minimum height of the blasted ore pile that forms over the crown pillar, based on the design of the extraction level and the expected primary fragmentation.
2. Use FlowSim BC®, a gravity flow simulator as a tool to simulate the concept model of the study. This in order to quantify the impact of the variables mentioned previously in terms of the tonnage required to achieve the necessary air gap.
3. Analyze the results obtained in terms of number of passes (buckets) and swell extracted.

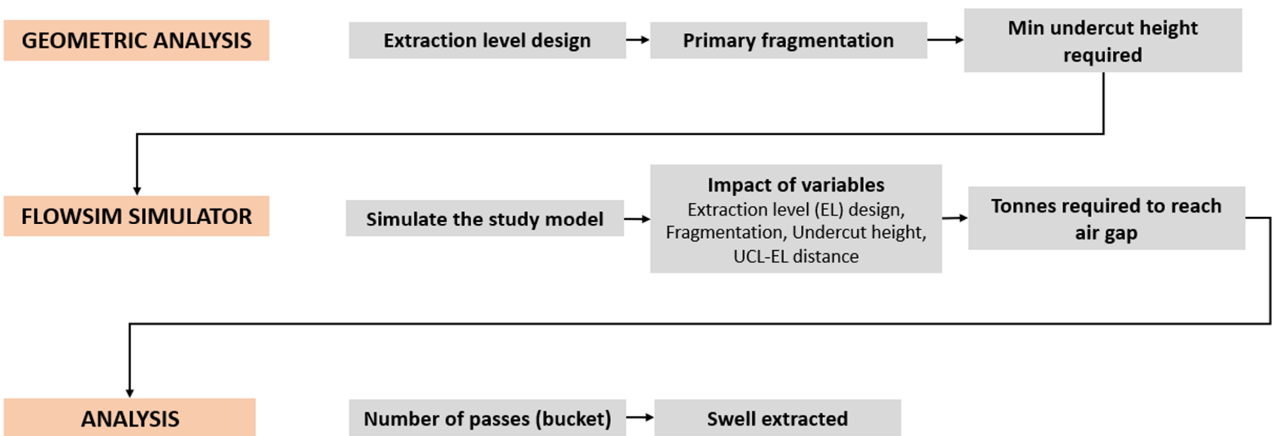


Figure 1 Methodology.

2.1 FlowSim BC® background

FlowSim BC® is a tool that allows modeling the gravity flow, which has been experimentally calibrated and validated in the mining industry and, which allows analyzing an extraction plan in terms of mining recovery, dilution input, quantification of fine copper and extracted ore grade.

FlowSim BC® works based on a three-dimensional representation of equal size blocks with their attributes, corresponding to location coordinates, density, ore grade, dilution and fragmentation (d50). The simulation process consists of the rise of voids generated by the ore extraction from drawpoints based on the void diffusion mechanism.

This tool requires the following inputs:

- Extraction level design and drawbell geometry.
- Extracted tonnage by plan.
- Block model (in situ ore grade, d50).
- Fragmentation.
- Porosity of the mineral.

Among the inputs necessary for the simulation, of greatest interest in this study are the design and geometry of the drawbells and the fragmentation.

The mining design under which the study was carried out considers a post-undercutting strategy where extraction level is fully developed and the undercut is then advanced over the extraction level horizon and the drawbells are ready to receive the blasted undercut ore.

The geometry used by the simulator consists of a box-type geometry, without considering the connection distance between the drawbell roof and the undercut level (UCL). The main characteristics are specified in the following figure:

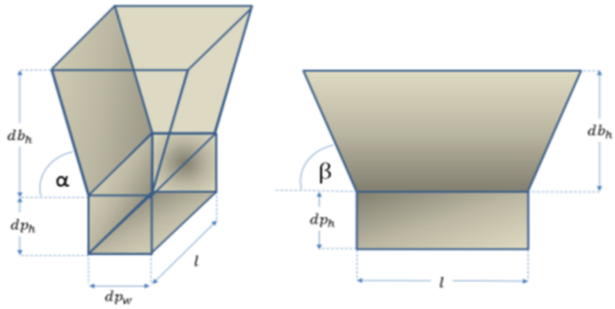


Figure 2 Geometry of the drawbell used in the simulation.

Where:

Dbh = Drawbell height

Dph = Drawpoint height

Dpw = Drawpoint width

α = Front angle (minor apex pillar)

β = Side angle (Crown pillar)

L = Drawbell length

Three extraction layouts were considered for the study, 32x20 m^2, 34x20 m^2 and 30x20 m^2 and the same drawbell geometry was considered. To evaluate the impact of the distance between levels, only the drawbell height was modified.

The parameters are shown in the following table as a summary:

Table 1 Drawbell geometry parameters for simulator

Parameter	Value	
UCL – EL distance (m)	18	25
Drawpoint width (m)	5	5
Drawpoint height (m)	4.75	4.75
Drawbell height (m)	9	16
Side angle (°)	89	89
Front angle (°)	58	71.7

A sector with 48 drawpoints and an area of 15,360 m^2 was considered for the study (see Figure 3). For the purposes of the simulation, the extraction plan of the first year of operation of the N2/N3 macro-blocks of the Chuquicamata Underground Mine was considered, as shown in

Figure 4. It should be noted that the application of this plan only has practical effects on the operation of the computational tool, since the application analysis of the undercut geometry will be carried out in terms of extracted tonnage and not of the extraction rate, so the results are independent of the extraction plan used.

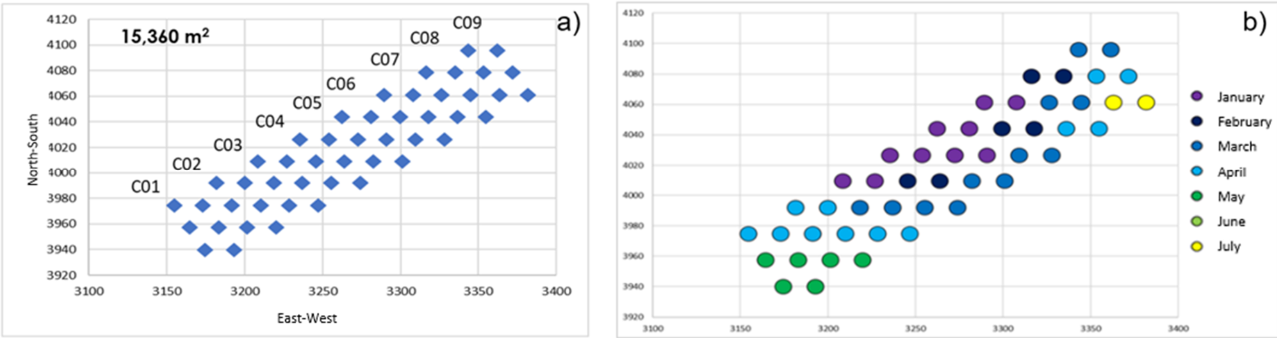


Figure 3 Drawpoints and extraction sequence – 32 x 20 m² layout.

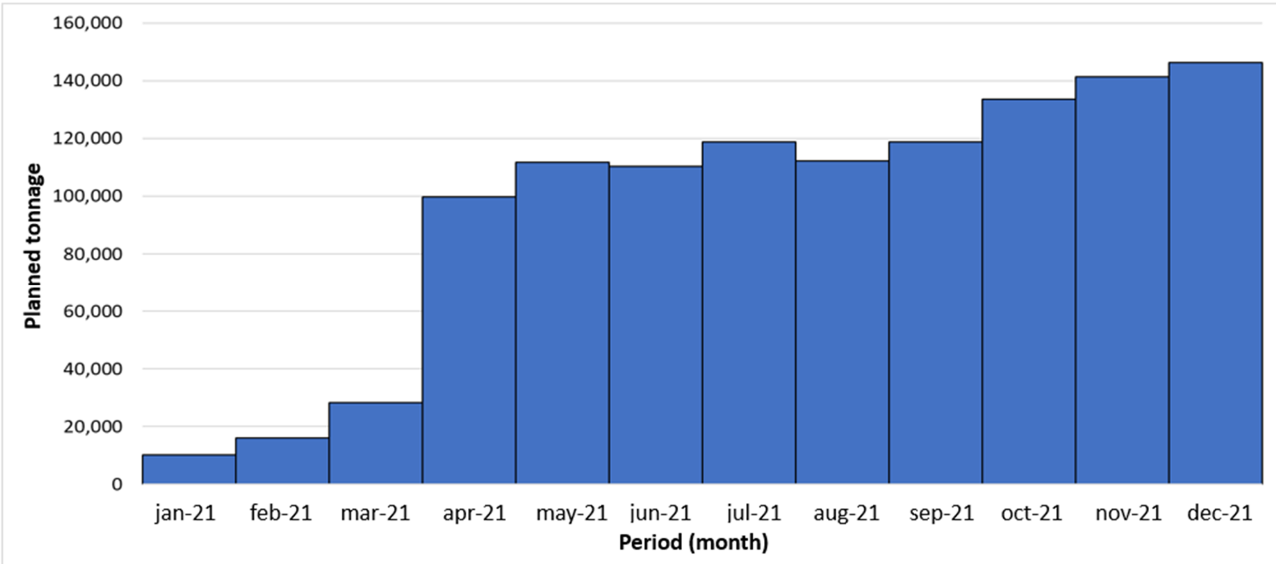


Figure 4 Extraction plan used to determine the tonnage needed to reach air gap

To emulate the incorporation of the different drawpoints under the undercut area, the different undercut heights were constructed defining the volume of material that is broken and has the capacity to flow. For the purposes of this study, heights of 10 m and 20 m were defined, incorporating drawbells according to the sequence presented in Figure 5. The following figure shows the incorporation into the simulation of the drawpoints in the indicated drawbell.

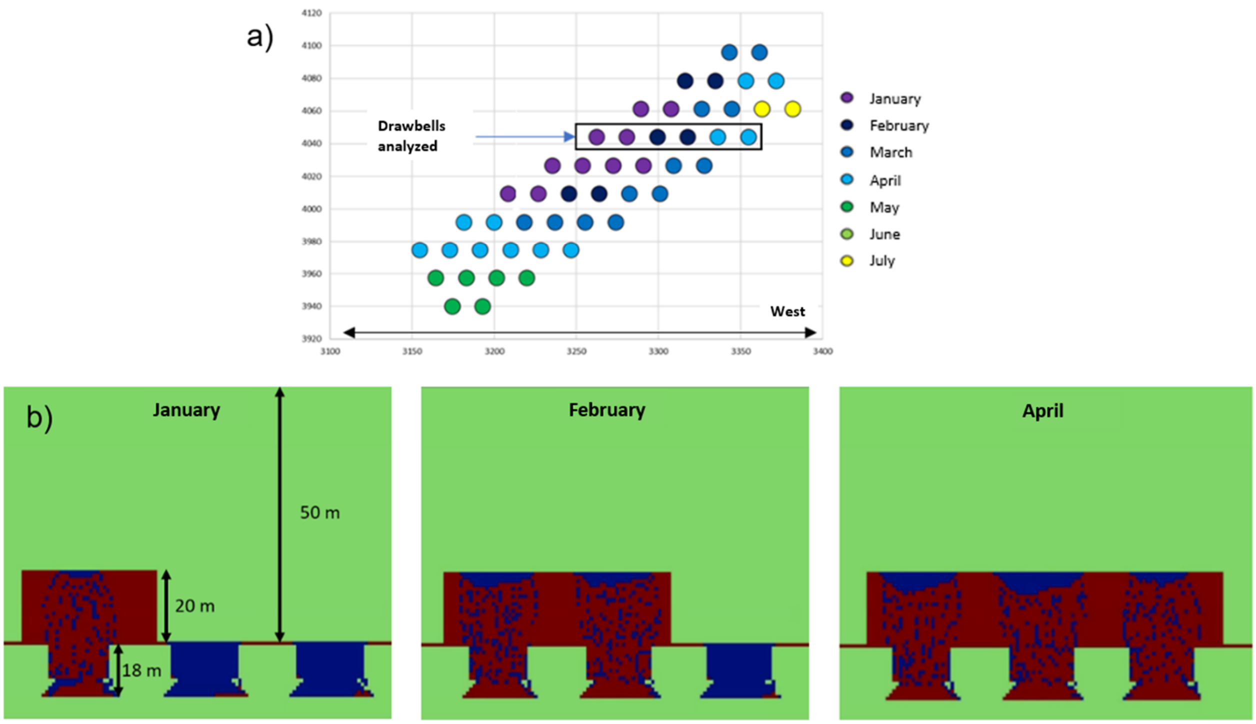


Figure 5 (a) Drawbells analyzed (b) Drawbell cross section for 32 x 20 m^2 layout. Undercut height: 20 m and distance between UCL-EL: 18 m.

2.2 Fragmentation and air gap

As a working assumption, it was considered that the space necessary to ensure the caving propagation is met when the air gap reaches 3 times the size of primary fragmentation. This criterion is comparable to the ore pass rules, which indicate that for a ratio between the diameter of the ore pass and the maximum size of the passing particle (D/d100) less than 3 there is no flow, between 3 and 5 there is intermittent flow. and greater than 5 the condition is free flow, (Castro, 2020).

For the analysis, 4 primary fragmentations were considered: 0.3 m, 1.0 m, 1.6 m and 2.3 m. According to the relationship mentioned above, the minimum air gap required are: 1.0 m, 3.0 m, 5.0, m and 7.0 m. In the following figure the void size that ensures the propagation of the caving for each fragmentation is shown.

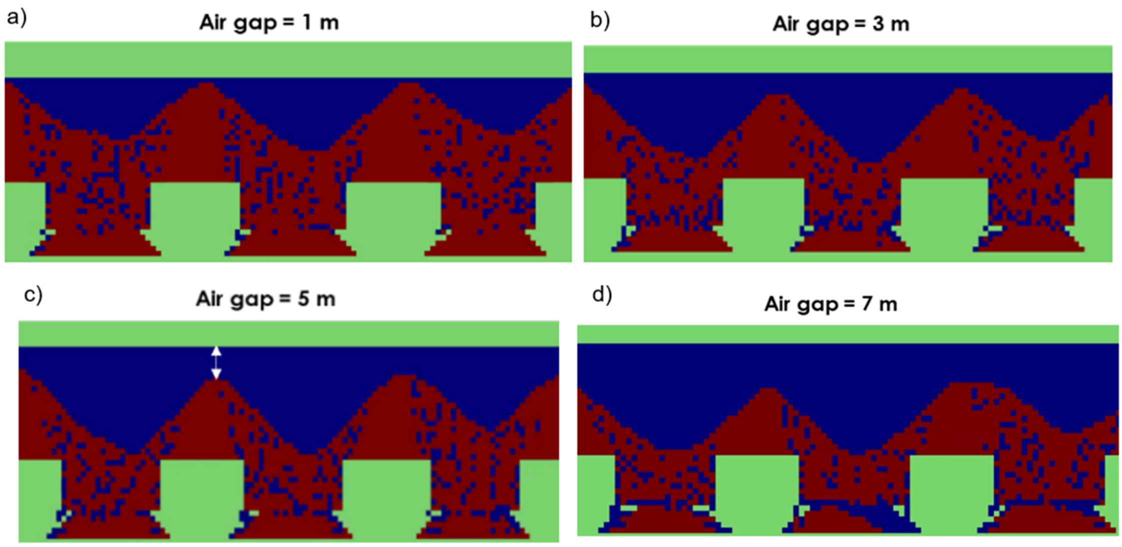


Figure 6 Air gap required for different fragmentations: (a) 0.3 m, (b) 1.0 m, (c) 1.6 m and (d) 2.3 m

3 SIMULATION RESULTS

A series of simulations were carried out using the FlowSim BC tool, seeking to emulate the initial stages of scour. A total of 42 scenarios were simulated where all possible configurations between the variables presented above were considered. The simulation plan is shown in Table 2.

Table 2 Simulation plan

Case	UH (m)	Layout (m^2)	UCL-EL	P(80) (m)	Air gap (m)
1	20	32x20	18	2.3	7
2	20	32x20	18	1.6	5
3	20	32x20	18	1	3
4	20	32x20	18	0.3	1
5	20	32x20	25	2.3	7
6	20	32x20	25	1.6	5
7	20	32x20	25	1	3
8	20	32x20	25	0.3	1
9	20	34x22	18	2.3	7
10	20	34x22	18	1.6	5
11	20	34x22	18	1	3
12	20	34x22	18	0.3	1
13	20	34x22	25	2.3	7
14	20	34x22	25	1.6	5
15	20	34x22	25	1	3
16	20	34x22	25	0.3	1
17	20	30x20	18	2.3	7
18	20	30x20	18	1.6	5
19	20	30x20	18	1	3
20	20	30x20	18	0.3	1
21	20	30x20	25	2.3	7
22	20	30x20	25	1.6	5
23	20	30x20	25	1	3
24	20	30x20	25	0.3	1
25	10	32x20	18	1.6	5
26	10	32x20	18	1	3
27	10	32x20	18	0.3	1
28	10	32x20	25	1.6	5
29	10	32x20	25	1	3
30	10	32x20	25	0.3	1
31	10	34x22	18	1.6	5
32	10	34x22	18	1	3
33	10	34x22	18	0.3	1
34	10	34x22	25	1.6	5
35	10	34x22	25	1	3
36	10	34x22	25	0.3	1
37	10	30x20	18	1.6	5
38	10	30x20	18	1	3
39	10	30x20	18	0.3	1
40	10	30x20	25	1.6	5
41	10	30x20	25	1	3
42	10	30x20	25	0.3	1

The simulation allowed to identify the role of each design variable regarding the necessary tonnage until the required air gap is achieved. The results of the simulations are provided in terms of the tonnage necessary to empty the drawbell (Tb), tonnage necessary to reach the air gap (Tg) and total extracted tonnage (Tt), the latter corresponding to the sum of Tb and Tg.

As a preliminary result obtained directly from the result of the simulations in terms of tonnage, the following can be observed (see Figure 7):

- An extraction layout with greater spacing between drawpoints requires extracting a greater tonnage to achieve the same air gap.
- A greater distance between levels (UCL and EL) reduces the undercut tonnage that is required to be extracted to achieve the air gap.

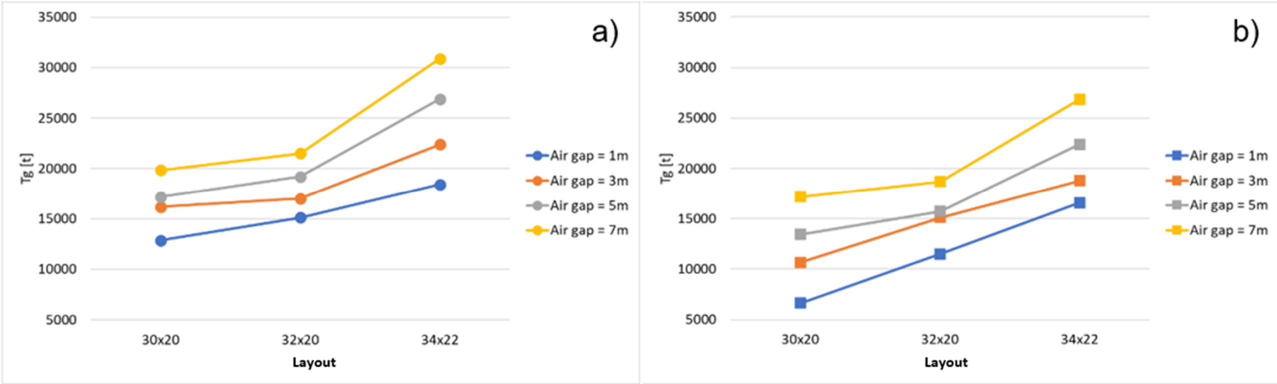


Figure 7 Tonnage required to reach air gap (T_g) according to the extraction level layout for an 18 m distance between levels (a) and 25 m (b). Undercut height of 20 m

On the other hand, in order to understand the influence of the scour height (10 m and 20 m), the following figure shows the tonnage required to form an air gap for the different extraction layouts.

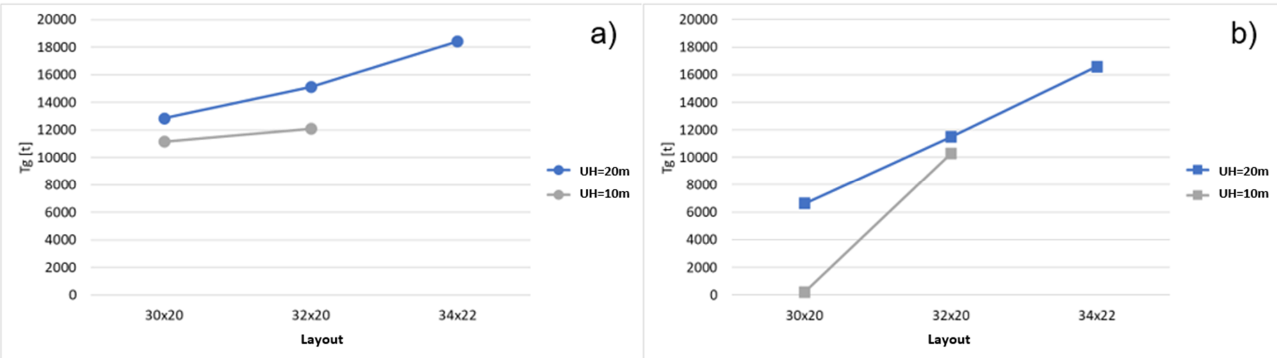


Figure 8 Tonnage required to reach air gap (T_g) of 1 m according to the extraction level layout for an 18 m distance between levels (a) and 25 m (b)

From these graphs, first of all, the trends of required tonnage depending on the dimension of the extraction level layout and the distance between levels are confirmed. Secondly, it is concluded that a greater undercut height requires extracting a greater tonnage to achieve the same air gap.

It should be noted that the low tonnage required in the case of a 30 x 20 m^2 layout and an undercut height of 10 m, corresponding to 208 t (Figure 8 – b), is due to the assumption that the drawbells are initially empty and due to the distance between levels for this scenario is 25 m, much of the blasted volume for an undercut height of 10 m is received by the volume of the drawbell.

4 ANALYSIS

4.1 Number of buckets

Based on the simulation results, a sensitivity analysis was carried out in terms of the number of buckets (passes) and number of days necessary to achieve the air gap.

Using the amount of tonnage necessary to achieve the air gap, the total number of buckets required per drawbell was calculated, considering an LHD shovel with a capacity of 21 tons and a filling factor of 80%. The results are shown in Table 3.

Table 3 Number of buckets

Case	T_g (ton)	# of bucket per drawbell
1	21,522	1,282
2	19,189	1,143
3	17,013	1,013
4	15,117	900
5	18,684	1,113
6	15,719	936
7	15,115	900
8	11,486	684
9	30,880	1,839
10	26,884	1,601
11	22,402	1,334
12	18,428	1,097
13	26,881	1,601
14	22,399	1,334
15	18,792	1,119
16	16,589	988
17	19,861	1,183
18	17,183	1,023
19	16,178	963
20	12,852	766
21	17,180	1,023
22	13,454	801
23	10,652	635
24	6,634	395
25	NF (*)	N/A
26	NF	N/A
27	12,093	720
28	NF	N/A
29	NF	N/A
30	10,280	612
31	NF	N/A
32	NF	N/A
33	NF	N/A
34	NF	N/A
35	NF	N/A
36	NF	N/A
37	NF	N/A
38	12,550	748
39	11,156	665
40	8,643	515
41	910	55
42	208	13

Tg: Needed tonnage to reach air gap per drawbell, (*) NF = Not feasible, N/A = Not apply

From these results, it is possible to analyze the time required to achieve an air gap under different conditions of extraction layout, undercut height, distance between undercut level (UCL) and extraction level (EL) depending on the number of buckets (passes) extracted per day per drawpoint.

The following graphs are presented as an example in Figure 9:

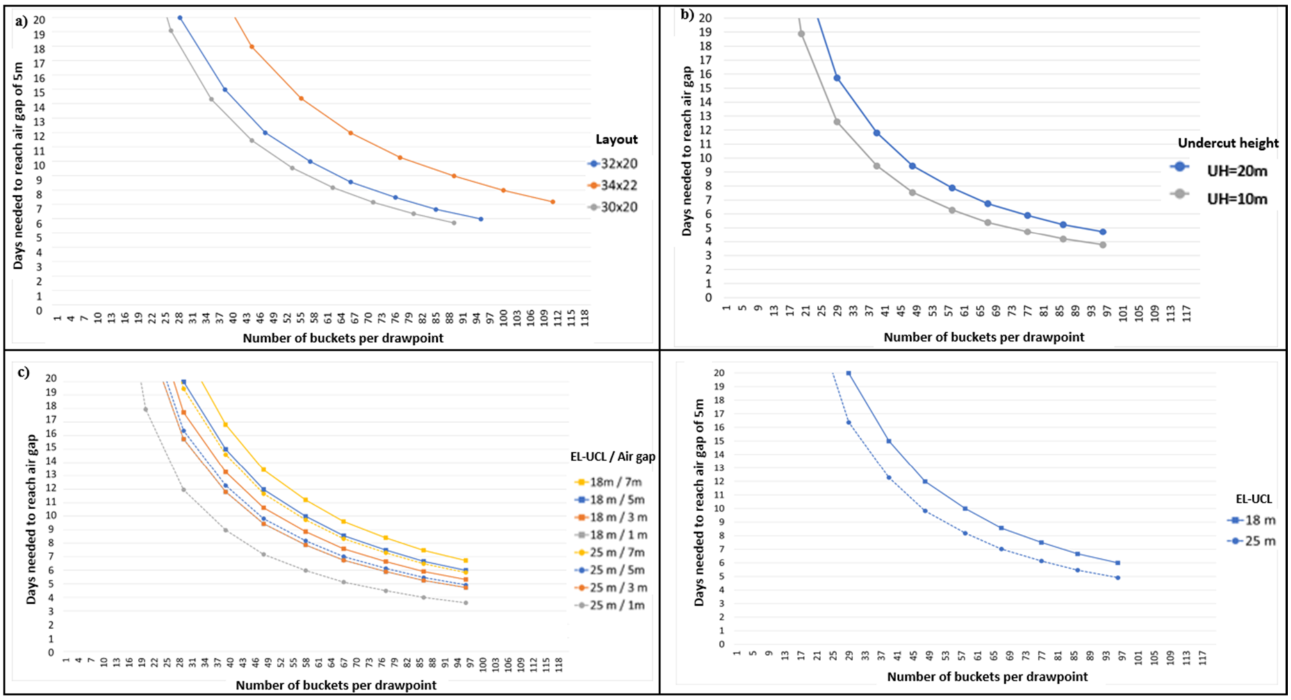


Figure 9 **Time required to reach air gap according to the number of buckets for different scenarios: a) extraction level layout, b) undercut height, c) and d) distance between EL-UCL and air gap.**

4.2 Swell tonnage extracted analysis

As part of the study, an analysis of the swelling removed until the target air gap was achieved in the simulation was carried out.

It is important to note that, for this analysis, the material was not completely removed from the drawbell and a pile of material equivalent to the volume of the drawbell was left, as indicated in Figure 10. The colored area represents the blasted volume that is not removed prior to undercut considering an angle of repose of 45° towards the drawpoints, which corresponds to an equivalent of 409 tons. Since the drawbell geometry does not vary for the different simulation cases, this value is applied to all the evaluated scenarios.

To quantify the swelling factor to be removed until the air gap is achieved, the in-situ undercut tonnage was estimated, which is defined by the colored area in the diagram of Figure 10, multiplied by the distance between drawbells for each layout and a rock density of 2.7 t/m^3.

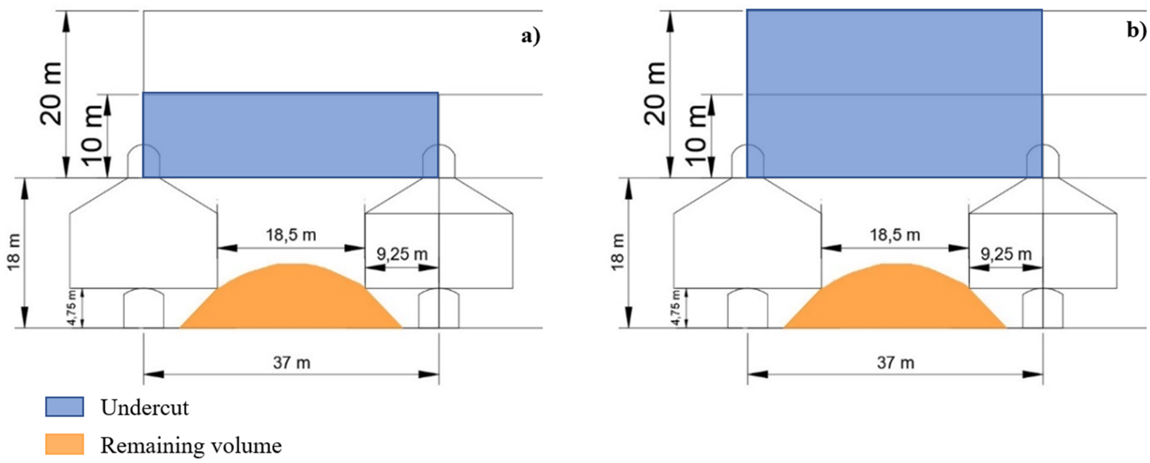


Figure 10 **Undercut in-situ tonnage per drawbell. Case corresponds to 32 x 20 m^2 layout, UCL-EL distance of 18 m. Undercut height: a) 10 m and b) 20 m**

Then, the simulated removed swelling was calculated as the ratio between the extracted tonnage required to reach the air gap Tg, presented in the previous section, and the in-situ tonnage Ti. The results are presented in Table 4. The table also shows the tonnage necessary to reach the air gap if a swell factor of 40% to be removed is considered.

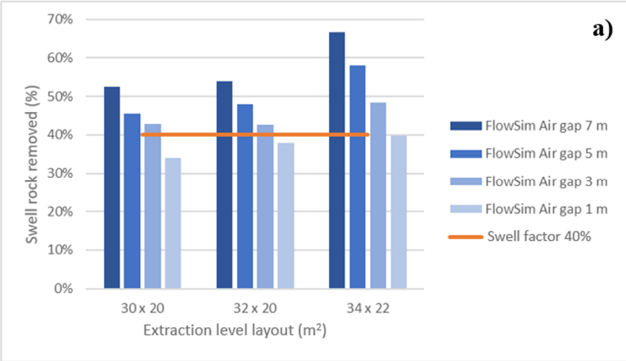
Table 4 Swell rock removed according to FlowSim BC® simulations

Case	Ti [t]	Tg [t]	Swell rock removed	Tg [t] (swell factor 40%)
1	39,960	21,522	54%	15,984
2	39,960	19,189	48%	15,984
3	39,960	17,013	43%	15,984
4	39,960	15,117	38%	15,984
5	39,960	18,684	47%	15,984
6	39,960	15,719	39%	15,984
7	39,960	15,115	38%	15,984
8	39,960	11,486	29%	15,984
9	46,332	30,880	67%	18,533
10	46,332	26,884	58%	18,533
11	46,332	22,402	48%	18,533
12	46,332	18,428	40%	18,533
13	46,332	26,881	58%	18,533
14	46,332	22,399	48%	18,533
15	46,332	18,792	41%	18,533
16	46,332	16,589	36%	18,533
17	37,800	19,861	53%	15,120
18	37,800	17,183	45%	15,120
19	37,800	16,178	43%	15,120
20	37,800	12,852	34%	15,120
21	37,800	17,180	45%	15,120
22	37,800	13,454	36%	15,120
23	37,800	10,652	28%	15,120
24	37,800	6,634	18%	15,120
25	19,980	NF(*)	N/A	7,992
26	19,980	NF	N/A	7,992
27	19,980	12,093	61%	7,992
28	19,980	NF	N/A	7,992
29	19,980	NF	N/A	7,992
30	19,980	10,280	51%	7,992
31	23,166	NF	N/A	9,266
32	23,166	NF	N/A	9,266
33	23,166	NF	N/A	9,266
34	23,166	NF	N/A	9,266
35	23,166	NF	N/A	9,266
36	23,166	NF	N/A	9,266
37	18,900	NF	N/A	7,560
38	18,900	12,550	66%	7,560
39	18,900	11,156	59%	7,560
40	18,900	8,643	46%	7,560
41	18,900	910	5%	7,560
42	18,900	208	1%	7,560

Tg: Tonnage required to reach air gap per drawbell,
(*) NF = Not feasible, cases where air gap was not reached.

The simulated swell factor value in FlowSim BC® is between a minimum of 1% and a maximum of 67%, with an average of 43%. According to these data, there is a high variability between cases, this is due to how the different variables evaluated affect the required tonnage to be removed. On the one hand, the highest values are associated with larger primary fragmentations, an extraction layout with greater spacing and a shorter distance between levels. For example, case 9, where 67% of swelling rock is removed, corresponds to the analysis of a layout of 34 x 22 m^2, distance between levels of 18 m, undercut height of 20 m and a fragmentation of 2.3 m, on the other hand, the cases at the other extreme, with less than 10% of swell rock removed, correspond to cases 41 and 42, which consider a lower undercut height (10 m), a greater distance between levels (25 m), and therefore more space available for the blaster ore to flow, and a finer primary fragmentation of 1 m and 0.3 m, respectively, and therefore a necessary air gap of lower volume.

The following figure shows the graphs of the simulated removed swelling rock for the three extraction layouts and for the different air gaps, for a 20 m undercut height.



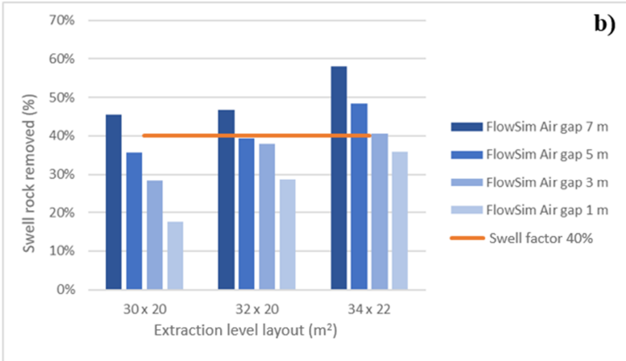


Figure 11 Swell rock removed according to extraction level layout. UCL-EL distance: a) 18 m and b) 25 m. Undercut height: 20 m.

From these it is observed that:

- A greater spacing between drawpoints, a greater percentage of the undercut swell rock must be extracted.
- For a greater distance between levels, less tonnage is required to extract to achieve the air gap, which means that less swell rock is removed.

Secondly, in Figure 12, the graph of the percentage of swelling rock removed in the simulation resulting from the extraction of the minimum undercut tonnage required to achieve an air gap of 1 m is presented based on the extraction layout design, considering a distance between levels of 18 m, for an undercut height of 10 m and 20 m.

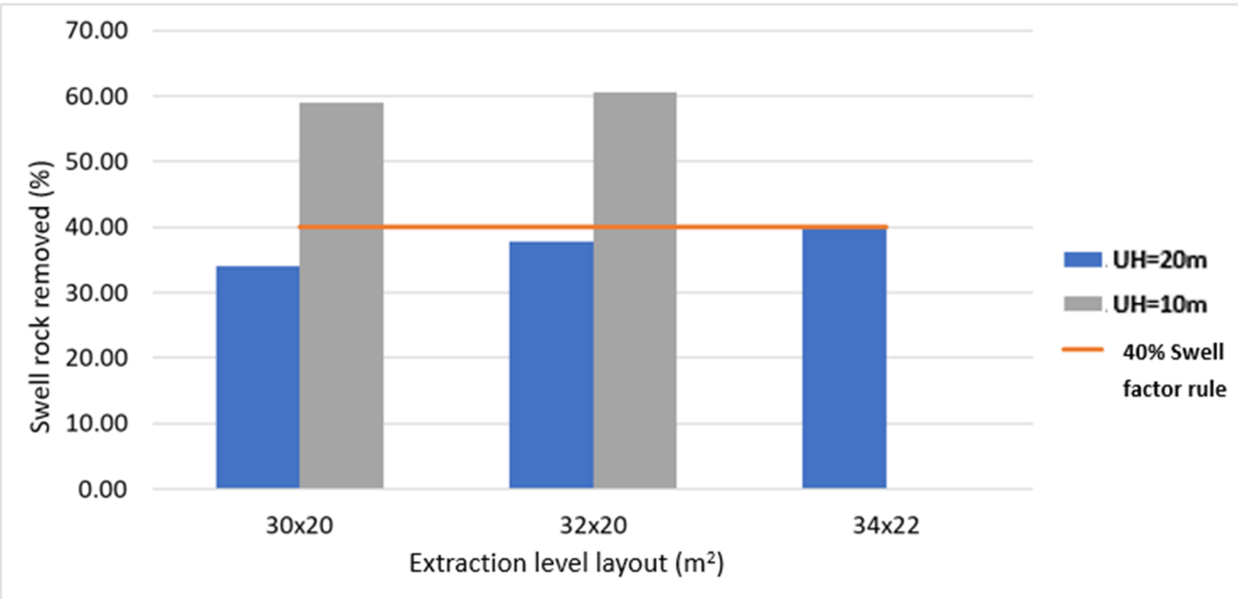
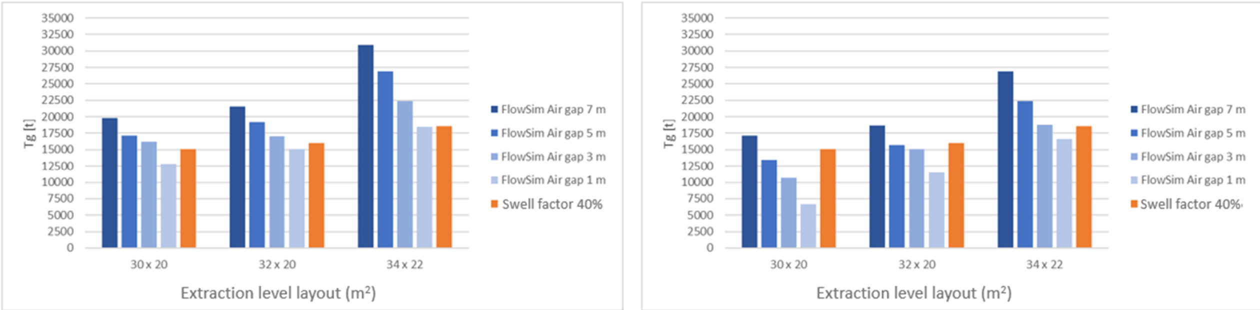


Figure 12 Swell rock removed to reach 1 m air gap according to the extraction level layout for 18 m distance between levels (UCL-EL).

A new aspect that can be observed in this graph is the impact of the undercut height variable; for a greater undercut height, a lower percentage of swell rock is removed to achieve the same air gap, close to 20% less.

The tonnage to be removed obtained by FlowSim BC® was compared with the swell factor to be removed equivalent to 40%. The graphs in Figure 13 present the comparison for a distance between levels of 18m and 25 m, respectively in both cases the analysis was carried out for an undercut height of 20 m.



Distance between levels of 18 m | Distance between levels of 25 m

Figure 13 Tonnage to be removed simulated with FlowSim BC® considering a swell factor of 40%.

For a distance between levels of 18 m, it is observed that the empirical rule of removing 40% of swell factor is met in those cases where an air gap of 1 m and 3 m is required. For air gaps of 5 m and 7 m, the amount of swelling factor to be removed is greater regardless of the spacing between points.

For a distance between levels of 25 m, it is observed that, for a greater distance in the 32x20 m^2 layout, the swelling removed in FlowSim BC® is more similar to the extracted tonnage equivalent to 40% of the in-situ tonnage. For a layout with a smaller spacing of 30x20 m^2, the graph indicates that the swelling necessary to remove to achieve air gap is less than 40% when the target air gap is 1 m, 3 m and even 5 m. Otherwise, for a layout with greater spacing it is necessary to extract greater swell when the air gap is 5 m and 7 m.

5 CONCLUSIONS

Firstly, it is concluded that, to determine the most appropriate undercut height for each operation, it is key to consider each of the variables studied, including the size of expected primary fragmentation, the layout design applied and the distance between the extraction level and undercut level.

Regarding the simulation results, it was possible to conclude that:

- The greater the spacing between drawpoints, the greater the tonnage required to extract to achieve the gap.
- Greater distance between levels affects the drawbell geometry and greater is the undercut blasted tonnage to be extracted to achieve the air gap.
- At a higher undercut height, a greater blasted tonnage is required to be extracted to achieve the required gap.
- Regarding the analysis of the number of shelves, it allowed the generation of design graphs for the different meshes evaluated. These graphs relate productivity in terms of the number of shelves to the number of days required to achieve the air gap.

From the analysis of the swell factor, it was observed that an extraction layout with greater spacing, a shorter distance between levels or a greater undercut height results in the extraction of a greater percentage of swelling to achieve the target air gap. According to the results obtained, the empirical rule of 40% is not applicable to all cases, and it is important to take into consideration the variables that are evaluated in this study when determining the swell factor to be extracted, highlighting the size of primary fragmentation and the distance between levels of the design.

Finally, this study helps determine the most appropriate undercut height given the design and fragmentation expected in an operation. In particular, the feasibility of application for undercut heights of 10 m and 20 m was analyzed, where in general terms a undercut height of 20 m allows greater flexibility in the design by extending the feasibility of its application to more design configurations and primary fragmentation ranges.

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REFERENCES

BCTEC. (2021). Benchmark of draw management and compliance in Block Caving operations. Internal report BCTEC (2021).

Butcher, R. (2000). Block Cave Undercutting - Aims, Strategies, Methods and Management. In MassMin 2000 (pp. 405-411). Brisbane, Australia: The Australian Institute of Mining and Metallurgy.

Brown, E. (2007). Block Caving Geomechanics, second edition. The International Caving Study 1997-2004, JKRMC University of Queensland.

Castro, R.L., López, S., Gómez, R., Ortiz, S. & Carreño, N. (2020). Experimental Study of the Influence of Drawbell Geometry on Hang-Ups in Cave Mine Applications. *Rock Mechanics and Rock Engineering*, 54, 1-10.

Duplancic, P. & Brady, B. H. (1999). Characterisation of caving mechanisms by analysis of seismicity and rock stress. In G. Vouille, & P. Berest (Eds.), International Congress on Rock Mechanics Proceedings (Paris, France ed., Vol. 2, pp. 1049-1053). CRC Press. Butcher, R., 2000. Block Cave Undercutting - Aims, Strategies, Methods and Management. En MassMin 2000 (pp. 405-411). Brisbane, Australia: The Australian Institute of Mining and Metallurgy.

Guzman, D. (2018). Analysis of the caving propagation and modelling using FlowSim BC. Undergraduated thesis, University of Chile, Chile, in Spanish.

Mullins, W. (1972). Stochastic theory of particle flow under gravity. *J. Appl. Phys*., vol. 43, no. 2, pp. 665–678.

Laubscher, D. (2000). A practical manual on Block Caving. Prepared for the International Caving Study (1997-2000), JKMRC and Itasca Consulting Group, Brisbane.