Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_48

Integrating gravitational flow and geomechanical analysis to the MBS05 of the Chuquicamata underground mine

Esteban Hormazabal [a,*], Giuseppe Barindelli [b], Edgar Montiel [a], Badih Rojas [b], Max Blondel [a]

[a] *SRK Consulting, Chile*

[b] *Codelco, Chile*

Abstract

In the practice of the geomechanical design of the extraction level of block caving mines, the spacing of drawpoints and production drifts is critical for life of mine footprint stability, gravitational flow, interaction of draw zone and reserve assumptions. This paper consolidates the results of the geotechnical and gravitational flow evaluation carried out for the Macroblock S5 (MBS05) of the Chuquicamata underground mine (MCHS) to optimise its current design. In particular, four designs corresponding to the El Teniente layout with dimensions of 15 × 22 m (15 m along production drifts and 22 m between drawbells drifts), 15 × 24 m (15 m along production drifts and 24 m between drawbells drifts) and with variants of crown pillar of 20 and 22 m in height for each case have been analysed. Gravitational flow studies were carried out with empirical methods and through simulations using Geovia PCBC software. The marker mixing (MMIX) algorithm was also used, which allows for modelling and for the simulation of various forms of mixing during ore extraction.

The performance of each design was analysed considering an approach based on local numerical models through the integration of a high-resolution mesh generator and the finite difference program FLAC3D. From the analyses carried out, design options were studied in terms of Factor of Safety and stress-strain response to the application of increasing loads on the pillars compared to the alternative designs. The selected design option was evaluated with an overall scale model incorporating the geotechnical model, geological faults, and excavation sequence of surface mining.

As part of this study, complex three-dimensional continuum models were developed and applied to evaluate the influence of the previously mentioned variables in the mechanical response of the underground workings, particularly, related to abutment stress developed in critical areas such as pillars and drawbells. This paper describes general and particular aspects of the MBS05, concentrating mainly on the rock mass behaviour of the operative MBs, using three-dimensional modelling.

Keywords: *numerical modelling, gravitational flow, extraction level design*

1 Introduction

The underground methods of block or panel caving is an exploitation method that is normally applied in disseminated deposits, located in depth, with a massive mineralisation of large dimensions; where the quality of the rock mass can show the prevalence of competent rock with a low frequency of fracture. In these high-stress environments, the mining method makes use of gravitational forces and the internal stresses of the rock mass to weaken and fracture the rock into smaller fragments. These fragments flow from upper levels to lower levels of the extraction drawpoints, which can be described as vertical movements and rotational movements inside an ellipsoid. Researchers have used scale sand models and simulations with the intention of studying the phenomena of gravitational flow and thus improving knowledge about how fragmented rock and particles behave during flow to the extraction drawpoint; formulating models, equations, and empirical design charts/rules that predict granular behaviour (Kvapil 1965, 1992; Janelid

* Corresponding author.

& Kvapil 1965; Laubscher 1994; Castro 2007; Castro et al. 2022). In addition, these studies provide initial design parameters and geometries relating to the spacing of openings (extraction drawpoints), diameters of the draw ellipsoids along with the flow of particles. These studies allowed researchers to develop a support tool for preliminary mine design (Laubscher 1990, 2001; Laubscher & Jakubec 2001; Laubscher et al. 2017 among others), specifically for the determination of extraction level geometry, being a primary support for the understanding of practical theoretical concepts of mine recovery and the behaviour and control of dilution in caving operations.

The Chuquicamata underground mine (MCHS) project, located in the Atacama Desert in northern Chile, is one of the largest mining projects in the world to use the method of block caving with macro-blocks option to mine copper and molybdenum. The operations began in the year 2019 with a projection of at least 40 years and a production regime of 140 ktpd. This article provides the results of the geotechnical and gravitational flow evaluation carried out for the Macroblock S05 (MBS05) of the Chuquicamata underground mine to optimise its current design.

2 Gravitational flow evaluation

2.1 Gravitational flow theory

Among the traditional researchers who have conducted studies in relation to the gravitational flow of particles, Rudolf Kvapil is the best recognised researcher (Kvapil 1965, 1992, 2004). Based on studies of mines exploited by sublevel caving (SLC) and empirical equations founded on that experience, Rudolf Kvapil proposes theories to size the diameter of the extraction ellipsoid (W_T) constructed on a curve that relates the extraction height (interaction height) with the theoretical extraction ellipsoid diameter (W’) in fine and coarse granulometry materials (Figure 1). Dennis Laubscher developed empirical design rules and curves that directs towards the determination of geometric parameters, relating the quality of the rock mass (RMR_{L90}, FF/m), the granulometry, the spacing between extraction drawpoints and the interaction height; proposing the concept of interactive draw based on the diameter of the isolated draw ellipsoid. Laubscher indicates that, for the existence of interaction between contiguous or adjacent extraction drawpoints, the spacing between them must be less than 1.5 times the isolated draw ellipsoid (Figure 2). Other researchers have also proposed theories (Richardson 1981; Just 1981; Rustan 2000), describing the phenomenon of gravitational flow in general terms, but without proposing empirical equations to determine or define the preliminary geometric parameters of the ellipsoids.

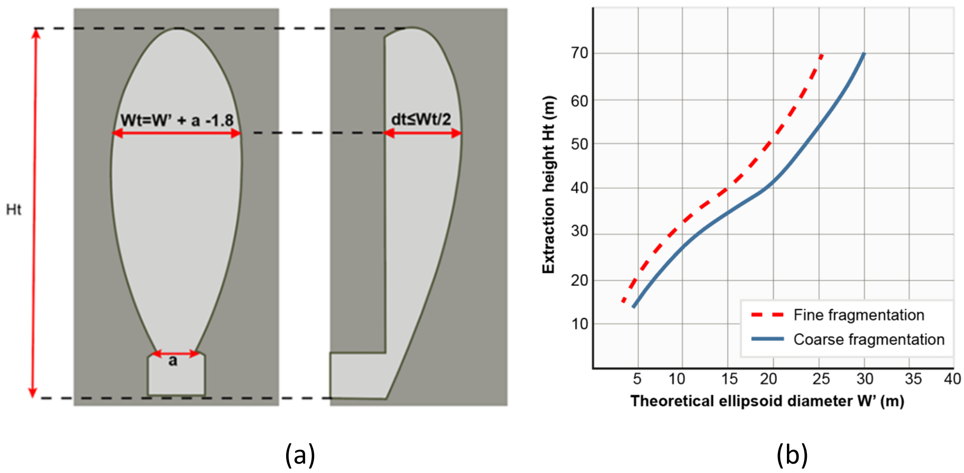
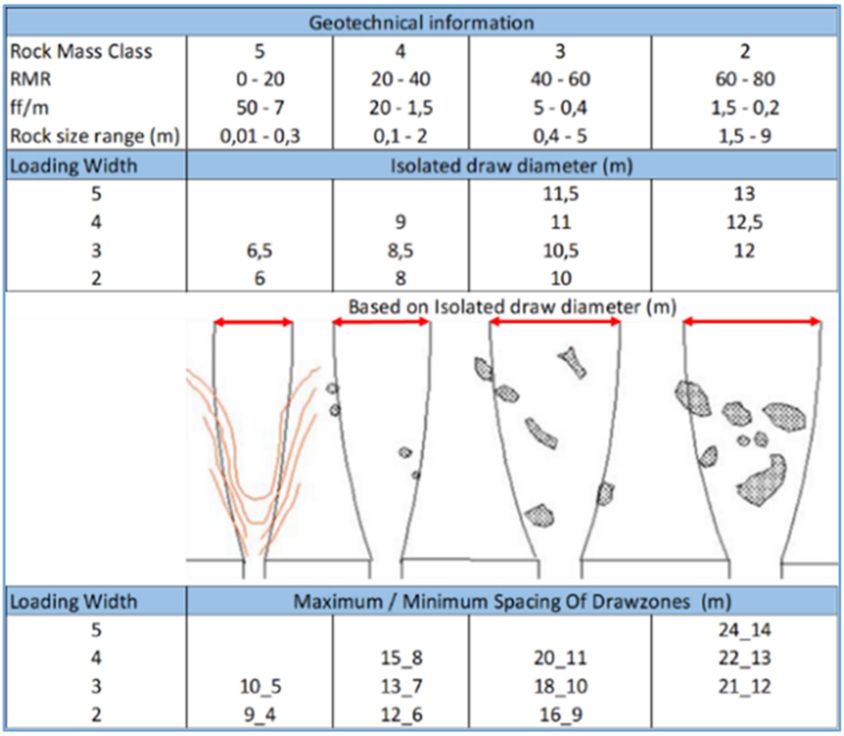
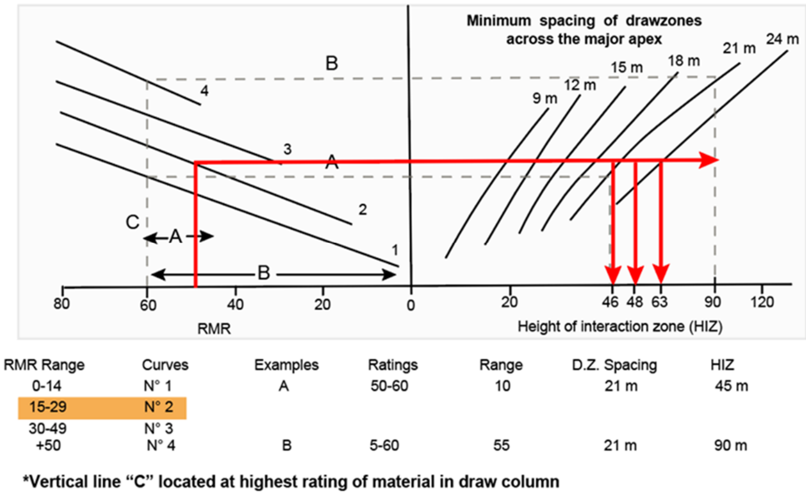


Figure 1 Correlations developed by Kvapil for gravitational flow. (a) Real ellipsoid diameter according to the theoretical diameter, W_T (modified from Kvapil 1998); (b) Extraction height (Ht) versus theoretical diameter W’ (modified from Kvapil 1992)



Geotechnical information				
Rock Mass Class	5	4	3	2
RMR	0 - 20	20 - 40	40 - 60	60 - 80
ff/m	50 - 7	20 - 1,5	5 - 0,4	1,5 - 0,2
Rock size range (m)	0,01 - 0,3	0,1 - 2	0,4 - 5	1,5 - 9
Loading Width	Isolated draw diameter (m)			
5			11,5	13
4		9	11	12,5
3	6,5	8,5	10,5	12
2	6	8	10	
Based on Isolated draw diameter (m)				
Loading Width	Maximum / Minimum Spacing Of Drawzones (m)			
5				24_14
4		15_8	20_11	22_13
3	10_5	13_7	18_10	21_12
2	9_4	12_6	16_9	

(a)



(b)

Figure 2 Correlations developed by Laubscher (1990) for mine design. (a) Isolated diameter concept and maximum and minimum spacing; (b) Interaction height (HIZ)

2.2 Empirical estimation of the extraction ellipsoid diameter and interaction height

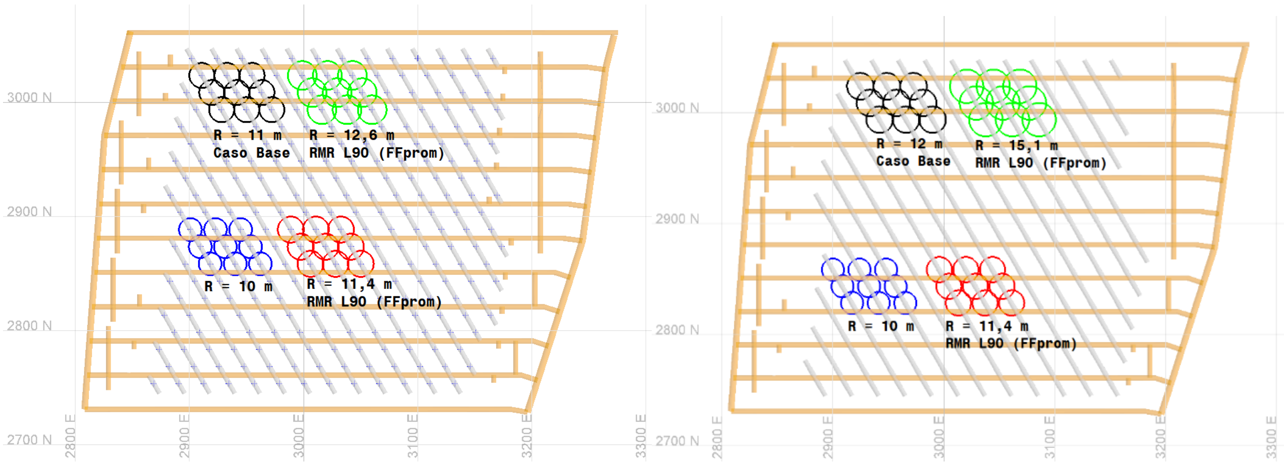
For the determination of the extraction ellipsoid diameter, the first consideration of Laubscher's design nomograms was applied. A Class II rock with the following characteristics was used for the analysis:

- an average RMR_{l90} = 47
- FF/m = range between 1.0–1.5
- rock size range between 0.75–2.50.

Input information was obtained from geotechnical mapping cells at drifts scale in the MBS04 extraction level with similar rock mass characteristics, which was used to determine the interaction height. These values correspond to the geotechnical unit quartz equal sericitic (QIS), which is chosen based on the criterion of being the most abundant in MBS05. By using this information, several configurations of extraction level design were analysed by these empirical methods and interaction height (HIZ) was calculated for each spacing with the corresponding theorical radius results (Table 1). Figure 3 shows the schematic geometrical configuration of ellipsoids for the extraction levels analysed.

Table 1 Results of the empirical methods applied to MBS05

Extraction level design (m)	Spacing (m)	HIZ (m)	W' (m)	W_T (m)	R_T (m)
15 × 20	20	46	21	22.7	11.4
15 × 22	22	48	23	25.2	12.6
15 × 24	24	63	28	30.2	15.1



(a) (b)

Figure 3 Schematic geometrical configuration of ellipsoids for extraction levels analysed. (a) Extraction level 15 × 22 m; (b) Extraction level 15 × 24 m

2.3 Gravitational flow simulation

To simulate the gravitational flow, Geovia PCBC software (Dassault Systèmes) was used, which works based on a column model derived from a block model. For this, a series of scripts must be executed that allow changing the support length from a model of regular blocks to a column model, which is configured and composed of slices that have a height equal to the height of the blocks model obtaining an in situ column model; that is, no mixing or dilution algorithm has yet acted. Over the last decades, Geovia PCBC has developed and implemented different mixing tools and algorithms, with the aim of simulating the phenomenon of dilution of the extraction columns in the extractive process of the underground mining method block/panel caving. These mixing algorithms have evolved from vertical pre-mixing (VMIX), which simulates the mixing that occurs between slices within the same extraction column, to the current dilution algorithm called marker mixing (MMIX), which from the in situ column model, is capable of modelling a variety of mixing possibilities (as the mineral is extracted from the column) such as vertical and horizontal mixing, inclined, sliding, erosion, collapse, etc. For the simulation, the latest dilution algorithm MMIX was applied to dilute the model and simulate the flows or extractions outlined in the Base Case production plans for the meshes studied, with geometric configurations of 15 × 22 and 15 × 24 m.

In addition to the plans for the indicated meshes, simulations and extraction sensitivities were carried out assuming a 15 × 20 m mesh. This mesh represents the 'theoretical optimum', determining a theoretical spacing between maximum extraction drawpoints of 20 m with an ellipsoid radius of 11.4 m (Table 1 and Figure 3).

2.4 Production plan simulations

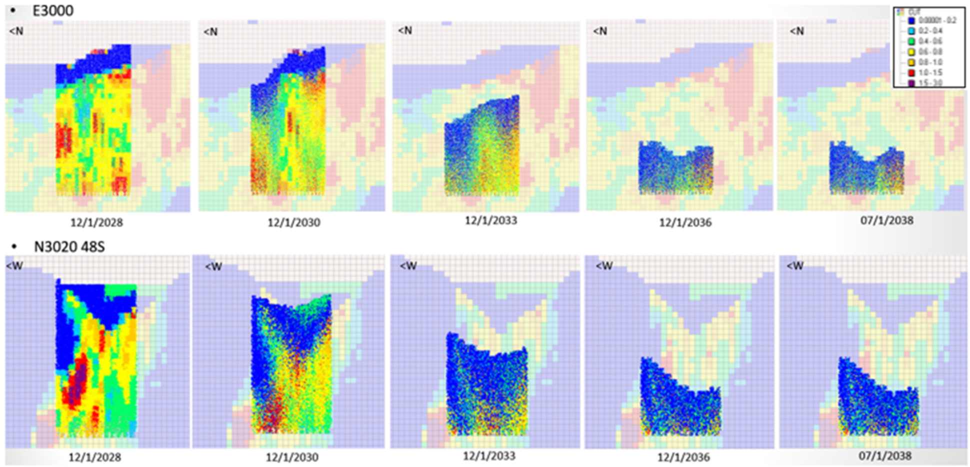
The objective of the extraction simulation is to study the extraction plans (Base Case) associated with the extraction levels configurations of 15 × 22 and 15 × 24 m for MBS05. These extraction plans, called Base Cases, correspond to the long-term production plans of MBS05 at MCHS. As previously mentioned, for the production plans to be simulated they must consider the tonnage extracted per month and per extraction drawpoint, the same constructed drawbell rate per month and consequently consider the sequence of area incorporation (m^2/month). It is important to highlight that the average total copper (CuT) grade of the Base Case plans to be studied is the result of the dilution of the block model from a vertical mixing algorithm. To replicate the Base Case plans, three production plans per extraction levels were simulated, assessing for each simulation, the HIZ and the radii of the respective extraction ellipsoids, but considering, (as indicated previously) the monthly tonnages per extraction drawpoint, same drawbells rate per month of construction and consequently considering the sequence of area incorporation (m^2/month).

Table 1 summarises the HIZ and extraction ellipsoid radius used to simulate the flows and production plans by extraction level geometry. It is important to mention that the simulated production plans corresponding to the radii of 11 and 12 m are related to the design radii and, consequently, to the distance or separation of the extraction drawpoints of the same production drifts, for the 15 × 22 m and 15 × 24 m geometries, respectively.

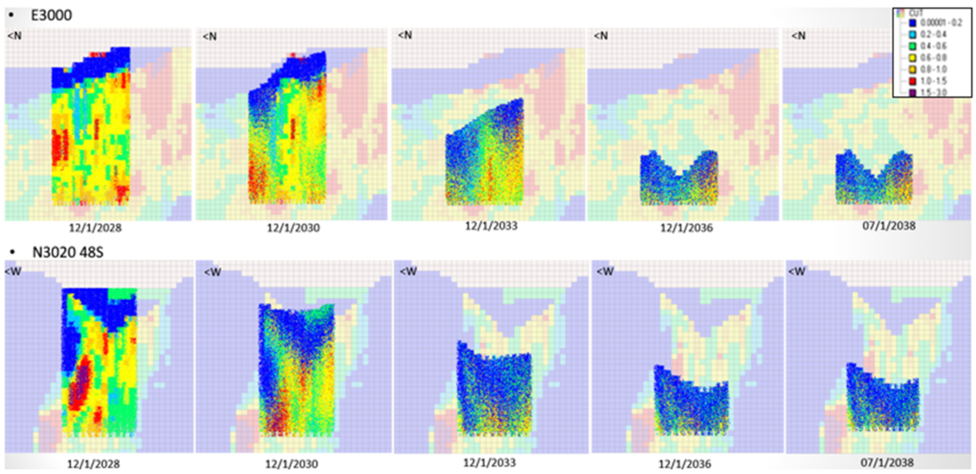
On the other hand, the simulated production plan with a radius of 11.4 m corresponds to the theoretical optimum radius that resulted from empirical analyses and that determines a spacing between maximum extraction drawpoints of 20 m (Figure 3). The simulated production plans corresponding to the radii of 12.6 and 15.1 m are related to the radii associated with the resulting interaction heights and according to the geomechanical parameters of MBS05, for the 15 × 22 m and 15 × 24 m extraction geometries, respectively. Finally, it should be noted that all simulations are performed from a model diluted with the MMIX dilution algorithm.

2.5 Simulations results

For the 15 × 22 m mesh, the simulations of production plans resulted in a 100% recovery of the mineral reserves and an average CuT grade of 0.714%, values that are consistent with the Base Case plan. Regarding the presence of diluting mineral or overburden, these simulations show on average 17% less diluting material compared to the Base Case, which is equivalent to −1,017 kt of material from the overburden existing in the open pit and the waste material near the West fault. In terms of fine copper, they contribute on average an additional 596 t of contained fine copper. According to the previous results, it is evident that the simulations carried out and their respective sensitivities in terms of interaction height and extraction ellipsoid radius, indicate that, on average, the mesh associated with the 15 × 22 m geometric design presents better indicators than the 15 × 24 m mesh. This is mainly evident because, in the results of the flow simulations, the 15 × 22 m mesh shows better indicators in terms of average CuT grade, contained fine and grade of diluting or broken material. In terms of recovered tonnage, the 15 × 22 m mesh recovers 2.2% more mineral, which is equivalent to an additional 2,072 kt with an average grade of 1.07% CuT. In terms of contained fine, the flow simulations indicate that the 15 × 22 m mesh contributes 3.4% more fine, which represents an additional contribution of 22,261 t of contained fine copper. Regarding the tonnage of diluting or broken material, the 15 × 22 m mesh contributes 0.7% more of this material compared to the contribution of the 15 × 24 m mesh, which is equivalent to an additional 36 kt, however, this additional contribution is only 0.04%, being a marginal value compared to the total mineral recovered by the 15 × 22 m mesh. Figure 4 shows the resulting grade profile of the simulations for the 15 × 22 m and 15 × 24 m meshes according to their respective design radii of 11 and 12 m. In addition to following the trend of the Base Case grade profile, it also maintains a higher value than that of the 15 × 24 m mesh for most of the production cycle. The above described reaffirms the better performance of the 15 × 22 m mesh compared to the 15 × 24 m, which ultimately - together with the higher mining recovery - results in a higher contained fine.



(a)



(b)

Figure 4 Simulation results obtained by the MMX dilution algorithms. (a) Extraction Level 15 × 22 Radii 11 m; (b) Extraction Level 15 × 24 m Radii 12 m

3 Geomechanical analysis

With the aim of analysing the theoretical behaviour of the pillars at the production level of the MBS05, local 3D numerical model of the pillars were created based on the design geometries provided by the Codelco Division Chuquicamata. These simulations are capable of determining the response of each pillar, considering it as a basic unit. Thus, it is possible to evaluate the rock mass behaviour to the excavation of the production drifts, drawbells openings/construction, over-stresses by applying vertical loads as an approximation of the caving front (abutment stress) and the impact of the implementation of typical support; as well as their respective Factor of Safety (FoS). The selected design options were evaluated with the numerical model incorporating the geotechnical model, geological faults, and excavation sequence of the open pit.

3.1 Geotechnical units

The MBS05 consists of five geotechnical units distributed at the extraction level, with a predominance of the units corresponding to potassic east porphyry (PEK), QIS, and brecciated quartz (QzBx). The QIS geotechnical unit corresponds to the unit that presents the lowest rock mass strength within the MBS05 and represents approximately 44% of the pillars at the extraction level, therefore, the stability of the pillars in this unit is key to the future performance of the MBS05. Table 2 details the rock mass strength properties of the geotechnical units (Codelco 2023) based on the Hoek–Brown parameters (Hoek 2019).

Table 2 Rock mass properties of the main geotechnical units at the MBS05

Geotechnical units	Intact rock properties			Rock mass properties						
	Unit weight (g/cm^3)	σ_{ci} (MPa)	mi	GSI	mb	s	a	σ_{cm} (MPa)	Erm (GPa)	v
PEK	2.59	77.0	9.3	64	2.56	0.018	0.502	17.9	34.1	0.22
PES	2.62	65.9	19.6	61	4.86	0.013	0.502	19.9	28.7	0.22
PEC	2.61	76.4	15.0	61	3.72	0.013	0.502	20.4	22.6	0.22
QzBx	2.63	51.2	17.6	59	4.06	0.011	0.503	14.1	13.4	0.23
QIS	2.66	50.0	15.2	50	2.55	0.004	0.506	10.7	11.6	0.25

3.2 In situ stresses

For the stability analysis, an update of the current MCHS stress model was considered. This model has been developed from numerous overcoring tests and acoustic emission measurements in various sectors. A global three-dimensional model was built using Flac3D software, and the calibration of the stresses was carried out. The calibration results are shown:

$$\sigma_{zz} = 0.026 \times z \ (MPa) \tag{1}$$

$$\sigma_{xx} = Szz \times 0.71 \ (MPa) \tag{2}$$

$$\sigma_{yy} = Szz \times 0.94 \ (MPa) \tag{3}$$

where:

z = the depth in m. The depth of the production level is from 550 to 600 m.

3.3 Local tridimensional numerical modelling

The performance of the production level pillars of the MBS05 has been evaluated by generating local 3D models considering a continuous analysis approximation by finite differences using FLAC3D software (ITASCA 2012). The local models have a high-resolution, symmetrical mesh with an element resolution of 0.5 m using the software Griddle v2 (ITASCA 2020). The geometries of the pillars have been defined by the geotechnical department of MCHS and correspond to the following cases:

- extraction level of 15 × 22, crown pillar = 20 m
- extraction level of 15 × 22, crown pillar = 22 m
- extraction level of 15 × 24, crown pillar = 20 m
- extraction level of 15 × 24, crown pillar = 22 m
- in consideration of the stability condition of the QIS pillars in the 15 × 24 design, an additional assessment was conducted with a more robust pillar alternative case 15 × 26 crown pillar = 22 m.

The extension of the local model considers the unit defined by the drawbell pillar with its limits located in the middle of the adjacent gallery and production drift. Figure 5 details the location of the local model with respect to the overall design of the extraction level and its dimensions for the case of 15 × 22 crown pillar (CP) 22 m. The boundary conditions of the model are characterised by being fixed at the base and by implementing 'attach' elements on the lateral faces, which allows a symmetrical response of the model. This boundary condition is represented in Figure 5. A 5 m high strip has been defined in the upper sector of the model above the drawbells with high strength properties to allow the transmission of vertical stresses in cases of an application of increasing monotonic loads corresponding to the analyses presented in the following sections.

The local models consider four stages of calculations corresponding to the following sequence:

1. initial in situ stress convergence
2. drifts Excavation
3. drawbell N°1 construction
4. drawbell N°2 construction.

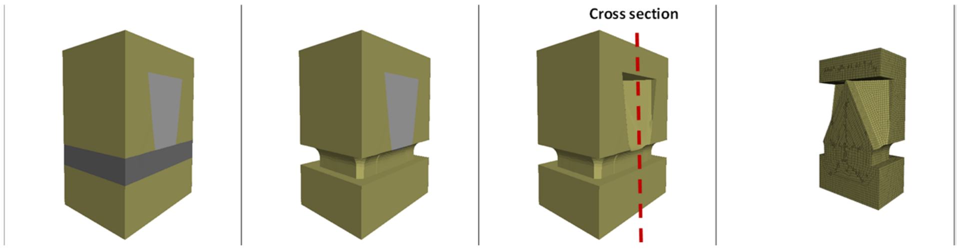


Figure 5 Local numerical model construction sequence

Additionally, support was included in sequential stages representative of the excavation considering equivalent internal pressures, p_i (Hoek 1999; Carranza-Torres & Fairhurst 2000a; Carranza-Torres & Fairhurst 2000b; Carranza-Torres & Fairhurst 2000c; Montiel et al. 2023a, among others) based on rockbolts (75 kPa), cables (155 kPa), concrete walls (205 kPa) and steel sets (1.1 MPa). Figure 6 shows the support application on the local model. Additionally, a sensitivity analysis was performed to assess the effect of the blasting damage (Montiel et al. 2023b). The results of these analyses are shown in Table 3. Results on the QIS unit shows that pillar size of 15 × 24 with a CP of 22 m is below the acceptability criteria (FoS < 1) so an increment in the pillar size is recommended for the QIS unit. Results for pillar size of 15 × 26 with a CP of 22 shows a FoS > 1.05.

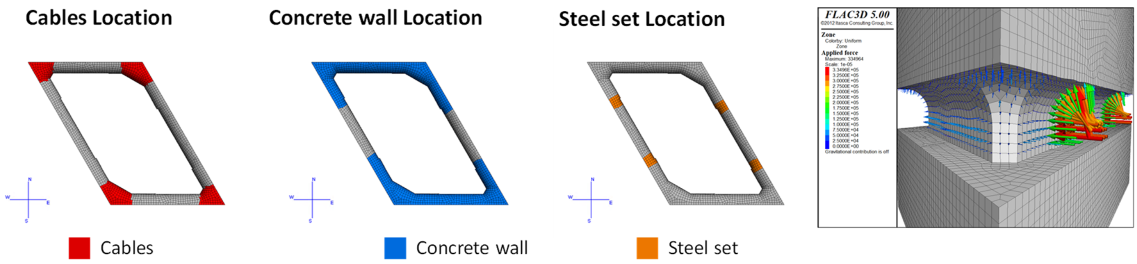


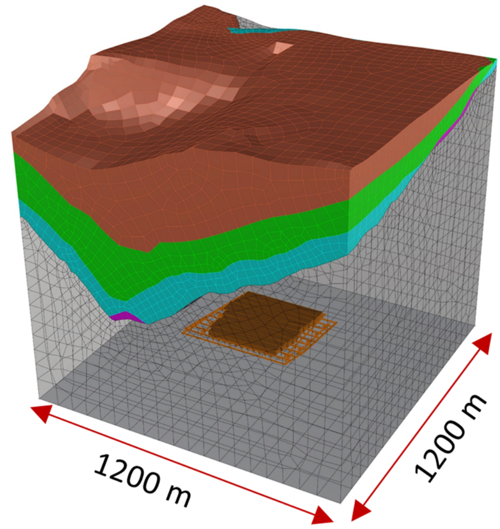
Figure 6 Local numerical model considering support based on the equivalent internal pressure, p_i

Table 3 Results of the local numerical modelling considering support

Geotechnical unit	D factor	Damage thickness (m)	Without support		With Support	
			FoS after drawbell N°1 excavation	FoS after drawbell N°2 excavation	FoS after drawbell N°1 excavation	FoS after drawbell N°2 excavation
QIS 15 × 24 CP 22	0	–	1.08	<1.0	1.12	<1.0
QIS 15 × 26 CP 22	0		1.16	1.0	1.20	1.05
PEK 15 × 24 CP 22	0	–	1.35	1.15	1.40	1.15
	0.5	0.5	1.30	1.10	1.35	1.15
		1.5	1.25	1.05	1.30	1.10
	0.7	0.5	1.30	1.10	1.35	1.10
		1.5	1.25	<1.00	1.25	1.05

3.4 Overall scale tridimensional numerical modelling

The performance of the pillars for the extraction level 15 × 24 design alternative with a 22 m CP of MBS05 was evaluated using an overall scale 3D numerical model, utilising the finite difference software FLAC3Dv7. The model covers an extension of 1,200 × 1,200 m and incorporates the open pit excavation sequences, as well as the geometries of the undercutting and extraction levels of MBS05, using the Griddle meshing software (Figure 7a). Differentiated element sizes are allocated according to the sector of interest: 0.5 m for the pillars of the extraction level, 1 m for the productions drifts and 2 to 4 m for the undercut level (UCL). Figure 7b details the sizes of the elements used for the construction of MBS05.



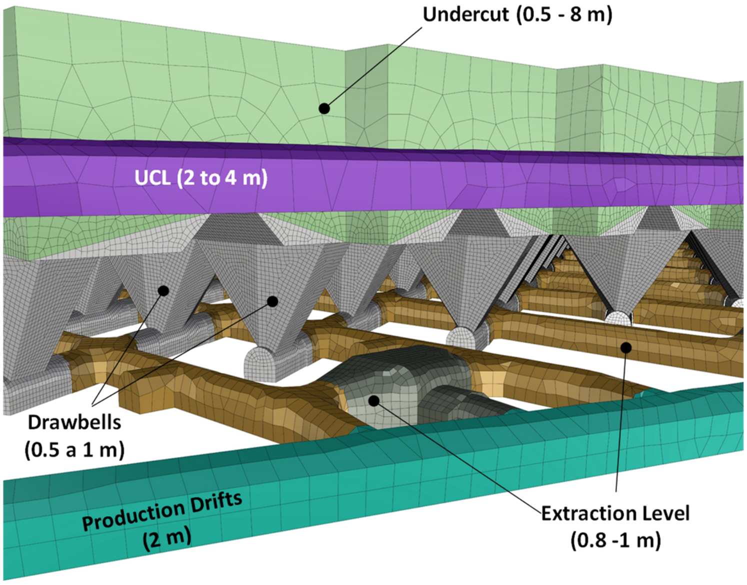


Figure 7 Overall scale tridimensional model MBS05. (a) Model dimensions. (b) Detail of the undercut level, drawbells and extraction levels (elements sizes in parentheses)

The model incorporates the current geotechnical units of MBS05 (Figure 8) and a total of 18 geological structures, which have been explicitly incorporated as interfaces, except for the West and American Faults which have been incorporated as a material with thickness, given the accumulated knowledge in the sector. The properties of the interfaces have been defined considering a cohesion of 40 kPa, friction angle of 25° based on historical back-analysis.

The initial stages of the analysis include the excavation sequence of the open pit until reaching the final pit condition, as well as the growth of the extraction of MBS04, adjacent to the analysis sector. Subsequently, the excavation of the UCL and extraction level (EXL) of MBS05 and the growth sequence of the macroblock are incorporated. The extraction surfaces have been adjusted to the heights of the production plan defined in Section 2.5, with a propagation ratio of 1:8 proposed from subsidence analysis and behaviour observed in other macroblocks in the sector. The undercutting sequence consists of 18 stages, Figure 8 shows only three stages for practical purposes. The sequence initially incorporates an area to the north of the macroblock, continuing to the south, and ending with the extraction of the central sector according to the Caving Rules Manual (Codelco 2021). This manual provides geotechnical recommendations to minimise the caving front extension, tonnage extracted per month and per extraction drawpoint, drawbells rate per month construction and the sequence of area incorporation (m^2/month) among others best practices rules.

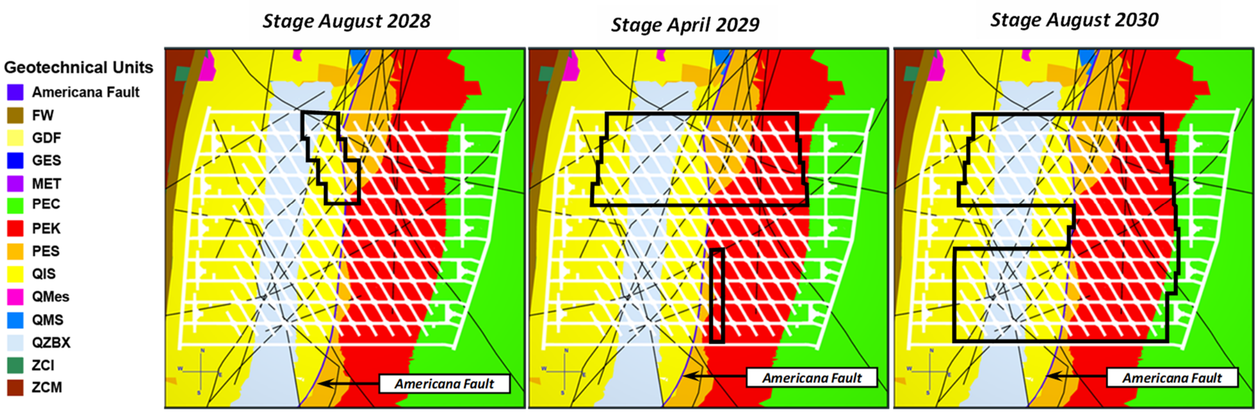


Figure 8 Geotechnical units, major geological faults and main undercutting sequence of MBS05 (plan view)

3.5 Assessment criteria for the extraction level layout

The stability in the pillars of the overall scale model has been estimated from the shear plastic strain (PSS) concept and its relationship with the local models where the FoS could be evaluated (Pardo 2015 among others). The contours regarding their calculated FoS are presented in Figure 9. It is observed that a PSS close to 1% corresponds to FoS slightly above equilibrium, while deformations greater than 2% in the depth of the pillar generate unstable conditions. Figure 9 shows the concordance of the PSS contours between the local and overall scale models. The mesh density in both cases allows these results to be comparable, while the overall scale model observes the effect of geological singularities such as faults or contacts between units with high strength and deformability contrast.

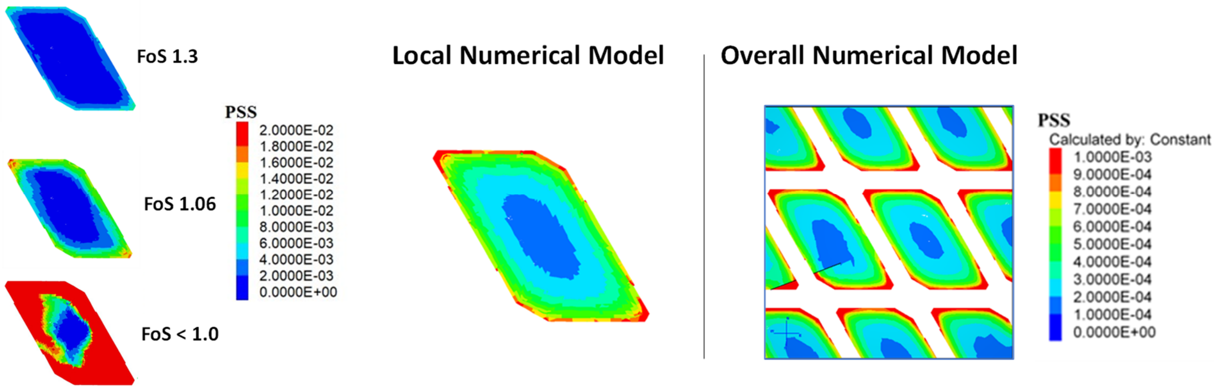


Figure 9 Shear plastic strain (PSS) comparison between local and overall scale models

3.6 Overall scale numerical modelling results

Before the undercutting and extraction level excavations, most of the pillars are shown to be stable (PSS < 1%). During the development process of the extraction, an increase in PSS is observed, becoming critical in the pillars located in the geotechnical units QzBx and QIS as well as those located in the American fault. This situation becomes significant as it represents 44% of the MBS05 pillars. Figure 10 shows the increase in the pillar damage due to the effect of the caving front, the proximity to the intersection of the Americana fault and the pillars located in the central part. The observed stresses in the model are shown in Figure 11, indicating sigma one values over 50 MPa and PSS over 2% locally. It is important to highlight that this analysis does not include damage by blasting; therefore, controlled blasting is mandatory in these sectors to avoid pillar and drift overbreak (Montiel et al. 2023b). The results from applying the overall scale model indicate the need to evaluate a more robust pillar size in the most critical sectors. This assessment should take into account gravitational flow analyses, economic costs, and operational viability, as well as the implementation of controlled blasting techniques in the weaker geotechnical units within the macroblock.

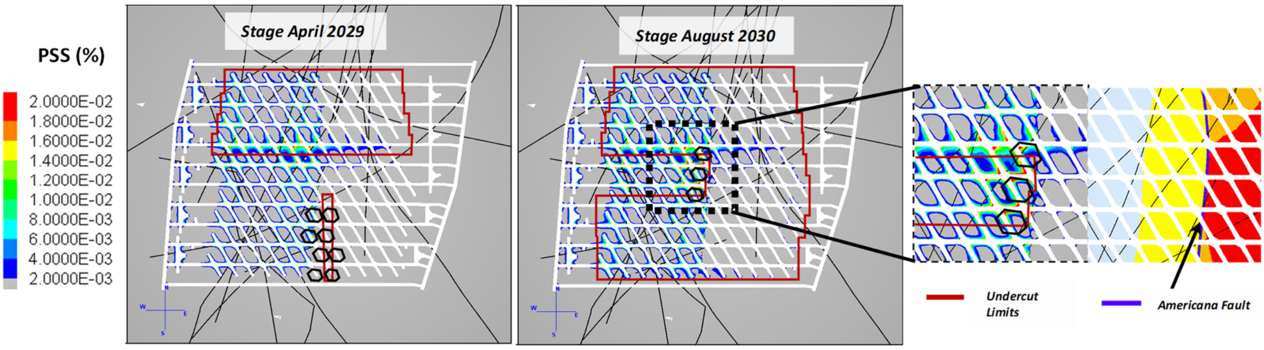
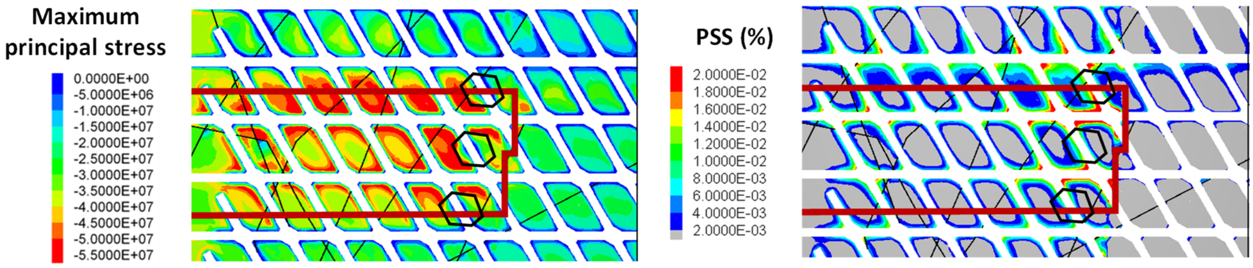


Figure 10 Shear plastic strain (PSS) evolution according to the mining sequence



(a) (b)

Figure 11 Details of the results in the central sector of MBS05 Stage August 2030. (a) Major principal stress; (b) Shear plastic strain (PSS)

4 Conclusion and final comments

Based on the classical empirical methods, it is observed that an increase in the spacing between extraction drawpoints, such as in a 15 × 24 m, leads to a greater interaction height. This implies that the relationship between the extraction drawpoints facilitates a more uniform flow of the ore from this interaction height. Once reached, the ore tends to flow in a more random manner as can be seen in the gravitational flow models. This phenomenon results in a more intense mixing of the ore during the extraction process, increasing dilution. Regardless of the fact that the 15 × 22 m grid shows the improved economic indicators compared to the 15 × 24 grid, in terms of gravitational flow and sensitivity of production plans (based on interaction heights and extraction ellipsoid diameters) it is necessary to compare and complement these results with stability analyses for the extraction level geometry optimisation and the cost of level development.

The pillars' performance under increasing loads applied to the 3D local numerical models has been evaluated incorporating indirectly the support based on rockbolts, cables, concrete walls and steel sets in order to assess the pillar stability. From the analysis carried out, it is observed that the support allows for an increase ranging close to 1 MPa in terms of pillar strength and results in an increase in the safety factor of ~0.05 in the analysed cases. Significant contribution to the pillar stability was observed when large and intense blast damage is included.

From the stability analysis using local models, a stable condition is observed in the pillars at PEK, PEC and PES units. The QzBx and QIS units represent geotechnical units relevant to the stability of MBS05, with critical behaviour observed in the case of QIS. FoS observed in these pillars (QIS) is close to the stability limit for operation. Exploratory analysis conducted on the pillar's performance in QIS with options for more robust dimensions such as the 15 × 26 CP 22 m or 16 × 24 CP 22 m designs provide an improvement of the pillar stability. From these analyses, it has been observed that increasing the width of the pillar by 2 m enables an increase in the pillar's stability, with FoS > 1.12 (case 15 × 26 m). Similarly, increasing the width of the pillar requires the selection of a new drawbell mining design. For this new mining design it would be important to study and evaluate both the overall stability analysis and their impact on gravitational flow, undercutting sequence and economic indicators.

References

Carranza-Torres, C & Fairhurst, C 2000a, 'Some consequences of inelastic rock mass deformation on the tunnel support loads predicted by the Einstein and Schwartz approach', in JF Labuz, SD Glaser & E Dawson (eds), *Trends in Rock Mechanics*, American Society of Civil Engineers, Colorado, pp. 16–49.

Carranza-Torres, C & Fairhurst, C 2000b, 'Application of the convergence-confinement method of tunnel design to rock-masses that satisfy the Hoek-Brown failure criterion', *Tunnelling and Underground Space Technology,* vol. 15, no. 2, pp. 187–213.

Carranza-Torres, C & Fairhurst, C 2000c, 'Analysis of tunnel support requirements using the Convergence-Confinement method and the Hoek–Brown rock failure criterion', *Proceedings of GeoEng2000, An International Conference on Geological and Geotechnical Engineering*, Technomic Publishing Co. Inc, Melbourne.

Castro, R 2007, *Study of the Mechanisms of Gravity Flow for Block Caving*, PhD thesis, The University of Queensland, Brisbane.

Castro, R, Gomez, RE, & Pérez, A 2022, 'Physical modelling as a tool to improve our understanding of mechanics of cave flow', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 1071–1088, https://doi.org/10.36487/ACG_repo/2205_74

Codelco División Chuquicamata 2021, '*Reglas del Caving, Mina Chuquicamata Subterranea' (Caving Rules, Chuquicamata Underground Mine)*, Informe GRMD-SGO-INF-007-2021.

Codelco División Chuquicamata 2023, '*Caracterización Geotécnica Macrobloque S05 Primer Nivel de Explotación Mina Chuquicamata Subterránea' (Geotechnical Characterization of Macroblock S05 First Mining Level Chuquicamata Underground Mine)*, Informe GRMD-SEG-INF-022-2023.

Hoek, E 1999, 'Support for very weak rock associated with faults and shear zones', in E Villaescusa, CR Windsor & AG Thompson (eds), *Rock Support and Reinforcement Practice in Mining*, Rotterdam, Balkema, pp. 19–32.

Hoek, E & Brown, E 2019, 'The Hoek–Brown failure criterion and GSI 2018 edition', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 3, pp. 445–463.

ITASCA 2012, *FLAC3D*, version 5.01.154.44151, computer software, Minneapolis.

ITASCA 2020, *Griddle (TM),* version 2.00.12, computer software, Minneapolis.

Janelid, I & Kvapil, R 1965, 'Sublevel caving', *International Journal of Rock Mechanics and Mining Sciences*, vol. 3, no. 2, pp. 129–153.

Just, GD 1981, 'The significance of material flow in mine design and production', in DR Stewart (ed.), *Design and Operation of Caving and Sublevel Stoping Mines*, Society of Mining Engineers, New York, pp. 715–728 .

Kvapil, R 1965, 'Gravity flow of granular materials in hoppers and bins', *International Journal of Rock Mechanics and Mining Sciences,* vol. 2, no. 3, pp. 35–41.

Kvapil, R 1992, 'Sublevel caving', in HL Hartman (ed), *SME Mining Engineering Handbook, 2nd Edition*, Society for Mining Metallurgy and Exploration, Littleton, pp. 1789–1814.

Kvapil, R 1998, 'The mechanics and design of sublevel caving systems', in RE Gertsch & RL Bullock (eds), *Techniques in Underground Mining – Selections from Underground Mining Methods Handbook*, Society for Mining, Metallurgy, and Exploration, Englewood, pp. 621–653.

Kvapil, R 2004, 'Gravity flow in sublevel and panel caving - a common sense approach', Luleå University of Technology Press, Luleå.

Laubscher, DH 1990, 'Mine design: a geomechanics classification system for the rating of rock mass in mine design', *Journal of the South African Institute of Mining & Metallurgy*, vol. 10, pp. 257–272.

Laubscher, DH 1994, 'Cave mining: the state of the art', *The Journal of The South African Institute of Mining and Metallurgy*, vol. 94, no. 10, pp. 279–291.

Laubscher, DH 2001, 'Cave mining – the state of the art', in W Hustrulid & R Bullock (eds), *Underground Mining Methods: Engineering Fundamentals and International Case Histories*, Society for Mining, Metallurgy and Exploration, Littleton, pp. 455–463.

Laubscher, D & Jakubec, J 2001, 'The MRMR rock mass classification for jointed rock masses', in W Hustrulid & R Bullock (eds), *Underground Mining Methods: Engineering Fundamentals and International Case Histories*, Society for Mining, Metallurgy and Exploration, Littleton, pp. 475–481.

Laubscher, DH, Guest, A & Jakubec, J 2017, *Guidelines on Caving Mining Methods - The Underlying Concepts*, WH Bryan Mining & Geology Research Centre, The University of Queensland, St Lucia.

Montiel, E, Jelicic, V, Trujillo, E, Hormazabal, E & Cabrera, J 2023a, 'Ground support assessment for a large crusher chamber', in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 255–268, https://doi.org/10.36487/ACG_repo/2325_17

Montiel, E, Blondel, M, Bustamante, E & Hormazábal, E 2023b, 'Effect of blast damage on pillars of caving mines', in W Schubert & A Kluckner (eds), *Challenges in Rock Mechanics and Rock Engineering: Proceedings of the 15th International ISRM Congress*, Austrian Society for Geomechanics, Salzburg.

Pardo, C 2015, *Back Analysis of Intensive Rock Mass Damage at the El Teniente Mine,* PhD thesis, Curtin University.

Richardson, MP 1981, 'Area of draw influence and drawpoint spacing for block caving mines', DR Stewart (ed.), *Design and Operation of Caving and Sublevel Stoping Mines*, Society of Mining Engineers, New York, pp. 149–156.

Rustan, A 2000, 'Gravity flow of broken rock — what is known and unknown', in G Chitombo (ed.), *Proceedings of MassMin 2000*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 557–567.