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Evaluation of the effect of wider-spaced layouts in recovery for high column block caves

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Abstract

Block caving has historically been the preferred underground solution to mine large, low-grade deposits (Laubscher 1994; Brown 2007; Chitombo 2010; Flores 2014). However, the caving industry has entered a less certain environment where some of the caving options are showing not to be fully suitable to achieving the envisaged low cost and high productivity (Flores 2019). This environment includes extreme conditions, i.e. deeper and blind deposits (>1,400 m from surface), lower grade, harder and heterogeneous rock masses, and higher in situ stress regimes (Flores 2019).

It is well understood that the major drawback of block caving is the high upfront capital cost and long lead time required to establish the cave. Establishment time and cost is exacerbated by increasingly complex orebodies at depth, including depth related issues such as low grades, strength/stress ratios, material handling costs and heat, among others (Flores 2014; Chitombo 2018; Ferguson et al. 2018; Flores 2019). The underground materials handling system and the footprint development and setup can represent above 50% of the direct capital cost for a new block (Paredes 2021). In this context, cave layout and materials handling system design are key levers to reduce tunnelling and timing requirements to establish a block caving operation. By reducing the overall tunnelling scope to establish a cave, the total exposure to risk of people and equipment, and establishment cost and timing can be consequently reduced.

Based on a critical literature review, one of the main gaps identified to enable the implementation of wider-spaced layouts (i.e. layouts that have wider spacing of extraction and drawpoint drives) that can be less intensive in development, is that: current methods to assess the gravity flow outcomes of block cave layouts in early engineering stages are based on physical experiments and empirical methods developed for low column heights in the 1990s and early 2000s. However, since then there has been significant progress in physical and numerical modelling of gravity flow, which can be used to quantify recovery and interaction for high column caves using wider-spaced layouts. Thus, this work aims to quantify the effect in recovery of wide-spaced layouts for deep and high-column caves based on mine data and the current state-of-the-art in flow modelling. This consisted of conducting a back-analysis of the Cadia East Mine data to understand the gravity flow behaviour and main flow parameters of a high column cave mine, with the aim to use these as the basis to quantify the effect in recovery of wide-spaced layouts using numerical and physical modelling. Subsequently, physical and numerical modelling (using both Cellular Automata and Kinematic approaches) was conducted to understand the effect on interaction and recovery of wider-spaced layouts and identify any potential fatal flaws. Results show that no fatal flaw in terms of interaction and recovery was identified by increasing drawpoint spacing beyond current industry practices, which presents an opportunity to evaluate wider-spaced layouts that are less intensive in development for deep and high column caves.

Keywords: *block caving, mine design, drawpoint spacing*

1 Introduction

The major drawback of the block caving method is the high upfront capital cost and long lead time required to establish the cave (Laubscher 2000; Brown 2007; Albanese & McGagh 2011; Flores 2014; Macquarie Research 2016; Chitombo 2018). Total development to establish a new cave including access can be over 220 km and take up to 14 years, with capital costs in the order of US$ 2B to US$ 10B (Macquarie Research 2016; Freeport 2018; S&P Global Market Intelligence 2020). Flores (2019) argues that the cave mining industry has recently entered a less certain environment where some of the cave mining options are already showing not to be fully suitable to achieving the envisaged low cost and high productivity. This environment includes extreme conditions, i.e. deeper and blind deposits (>1,400 m from surface), lower grade, harder and heterogeneous rock masses, and higher in situ rock stress regimes. In this environment, cave establishment time and cost are exacerbated by increasingly complex orebodies at depth, including depth related issues such as low grades, strength/stress ratios, material handling costs and heat, among others (Flores 2014; Chitombo 2018; Ferguson et al. 2018; Flores 2019). The underground materials handling system and the footprint development and setup can represent above 50% of the direct capital cost for a new block (Paredes 2021). In this context, cave layout and materials handling system design are key levers to reducing tunnelling and timing requirements to establish a block caving operation. By reducing the overall tunnelling scope to establish a cave, the total exposure to risk of people and equipment, and establishment cost and timing can be consequently reduced. Wider-spaced cave layouts can contribute to reduce the tunnelling scope and enable larger pillars to better withstand the increasingly challenging geotechnical conditions associated with increased depths.

Despite it being acknowledged that cave layout and materials handling systems (MHS) design are key levers to improving the block caving project's establishment cost and time, design practices have remained fundamentally unchanged since the early 2000s. The first compilation of the state-of-the-art in block caving practices was published by Laubscher in 1994 and republished in 2001. Charts and methods developed by Laubscher and published in this article were based on sand experiments and data of the mines being exploited at that time. This publication became the major reference for cave mining design (Chitombo 2010) and is still widely used to determine key design features such as draw zone (or drawpoint) spacing, dilution entry, and caveability for block caving projects. In 2001 and 2002, Flores & Karzulovic (2002) conducted a benchmarking study on cave mining practices in the context of the International Caving Study II (ICS II). According to Flores and Karzulovic's (2002) findings, in the early 2000s, the caving industry was exploiting and planning block heights below 500 m with an average of 210 m, with drawpoint spacing layouts in the range of 26 m to 34 m between extraction drives and 13 to 18 m between drawpoint drives. These extraction level layouts were all based on the use of LHDs with varying Herringbone and El Teniente layout styles.

During the early 2010s, as orebodies kept getting deeper and lower graded, the industry started looking at significantly greater block heights to improve the overall economic outcome (Manca and Flores 2013). In October 2014, Newcrest's Cadia East PC1 achieved the breakthrough to surface from approximately 1,200 m below assisted by intensive preconditioning (Lett et al. 2016). This marked a significant milestone for the block caving industry, as it was the first time a single block cave with a nominal height above 500 m was established. Also, Cadia East PC1 marked a benchmark in terms of planned nominal block heights with 1,050 m (Manca & Flores 2013). After the successful establishment of PC1, Newcrest developed and established Cadia East's PC2, located 200 m deeper than PC1 at approximately 1,400 m from surface, with a similar nominal height of draw to PC1 (Cuello & Newcombe 2018). Since Cadia East's PC1 successful establishment, a trend in the industry has been to increase the planned block heights from the typical 200 m practice of the early 2000s to over 500 m and up to 1,000 m in today's operations and projects (see Figure 1). However, as argued by Flores (2014), other key features of the cave layout design have remained fundamentally unchanged. Today's block caving projects are based on the use of LHDs to extract the ore from the drawpoints with extraction level layouts in Herringbone and El Teniente styles with similar spacing ranges to those in the early 2000s, as depicted in Figure 1.

In order to implement novel designs that can be less intensive in development and therefore enable safer, faster and lower cost, limiting factors in cave mine design need to be identified, and step change designs proposed. This paper addresses one of the limiting factors: drawpoint spacing limits for high column caves.

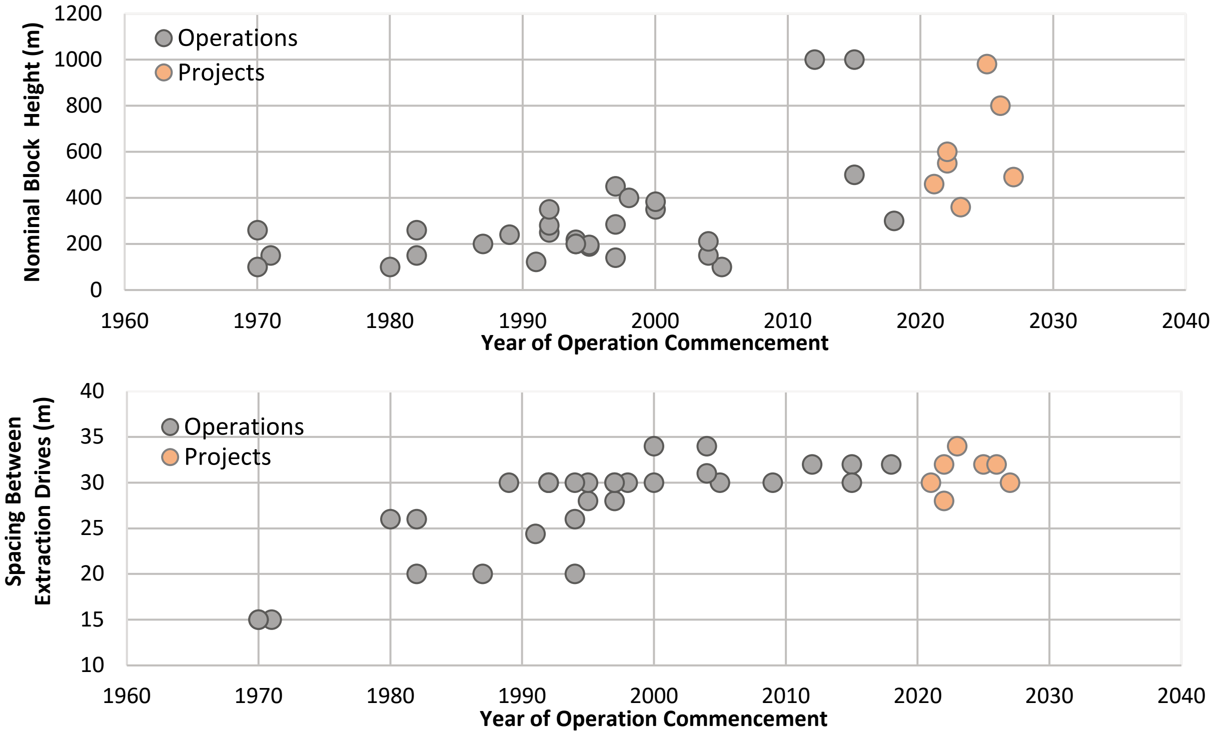


Figure 1 Evolution of the nominal block height and spacing between extraction drives (sources: Flores & Karzulovic 2002; Gaete et al. 2007; Codelco 2018; Callahan et al. 2008; Chadwick 2010; Callahan & Gillion 2012; Casten et al. 2016; Rio Tinto 2018; Sainsbury et al. 2016; Resolution Copper 2018; Codelco 2018; Paredes et al. 2018; Newcrest 2018; Flores & Catalan 2019; Newcrest 2019, 2020)

2 Limiting factors in cave layout design and state-of-the-art in flow modelling

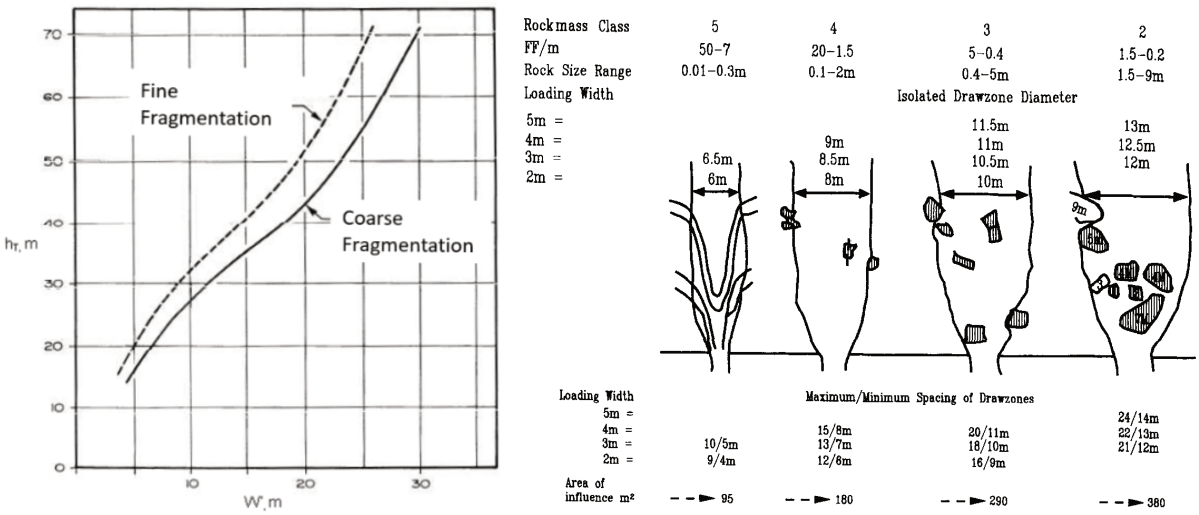
In order to determine which are the main limiting factors preventing the implementation of novel designs that can be less intensive in development and therefore enable safer, faster and lower cost cave establishment, a critical literature review was conducted. This literature review focused on three main areas: materials handling systems, undercutting methodologies, and gravity flow and drawpoint spacing determination. This paper focuses on the third area: gravity flow and drawpoint spacing determination.

The extraction level design has several objectives: it must be stable over the life of the mine, enable a high ore recovery and avoid excessive dilution, ensure a given production capacity, and have a capital and operational cost as low as possible (Laubscher 1994; Castro et al. 2012; Flores 2014). The selection of the layout design parameters is therefore a compromise between competing factors. The wider the drawpoints are spaced, the less excavations and construction is required to setup the area. Wider spacing also results in more robust pillars that can withstand higher stresses. However, implications of spacing the drawpoints in excess could result in low recovery and excessive dilution (Laubscher 1994; Van As & Van Hout 2008; Castro et al. 2012). It is through the understanding of how ore flow behaves that ore recovery and dilution can be estimated for different extraction level layouts (Marano 1980; Laubscher 1994; Castro 2006; Guest 2007; Pierce 2010).

Several authors coincide that draw zones will form inside the caved material muckpile, as a consequence of draw from the drawpoints below (Kvapil 1965; Marano 1980; Heslop and Laubscher 1981; Power 2004; Castro et al. 2007; Trueman et al. 2008). These draw zones consist of volumes of material moving downwards and sideways governed by gravity and other mechanical interactions. The gravity flow mechanisms that occur inside and in the surroundings of this draw zones have been hypothesised and tested by different authors throughout time. According to these authors, the variables influencing these mechanisms are; material properties (strength, cohesion, friction angle, particle shape, size and distribution), column height, cave propagation rate and shape, and draw strategy (Kvapil 1965; Laubscher 1994; Castro et al. 2007; Trueman et al. 2008; Pierce et al. 2003; Pierce 2010; Castro & Paredes 2014; Castro et al. 2018). The nature of the approaches to link these mechanisms and variables to generate predictive flow tools, and generate design guidelines, can be classified into two: (1) via physical and empirical models, and (2) via numerical models.

2.1 Physical modelling and empirical approach

The first attempt to convert gravity flow mechanisms in caved ore into a mathematical model was undertaken by Kvapil in 1965. Through scaled two-dimensional physical models using sand, Kvapil establishes two volumetric zones that form the basis of today's understanding of gravity flow: the extraction ellipsoid, or Isolated Extraction Zone (IEZ), and the loosening ellipsoid, or Isolated Movement Zone (IMZ). Later, Kvapil (1992), established a relationship between the heights and volumes of the IEZ and IMZ: the ratio between the IEZ and IMZ height being 1:2.5, and between their volumes being 1:15. Kvapil used an extension of his theory to determine block caving drawpoint spacing in the late 1980s by means of an equation that related the spacing to the loading width, the extracted volume, and the ellipsoid height. Later, Kvapil (2004) developed a chart to determine draw zone diameter as a function of fragmentation; however, no data to support the chart is presented (Figure 2).



(a) (b)

Figure 2 (a) Kvapil (2004) draw zone shape chart, W: draw zone width, Ht: drawzone height; (b) Drawpoint spacing abacus based on sand experiments (Laubscher 1994)

Heslop, Laubscher and Marano extend Kvapil's approach in scaled three-dimensional sand experiments, adding drawpoints, and varying the extracted mass and spacing between drawpoints (Marano 1980; Heslop & Laubscher 1981; Laubscher 1994). Based on these experiments, Laubscher (1994) argues that the IMZ will depend on the loading width and fragmentation, and also concludes that the formation of interacting draw zones will occur at a certain height, given certain drawpoint spacing, material fragmentation, and simultaneous draw conditions. This phenomenon is referred to as 'interactive flow' (Laubscher 2000; Guest 2007) and this height is defined by Laubscher (1994) as the 'height of interaction zone' (HIZ). These interacting draw zones will generate mass flow of the caved ore ultimately leading to higher recovery and less dilution than that expected from isolated draw zones (Laubscher 2000).

Laubscher (1994) presents an abacus to determine the HIZ, which depends on the ranges of rock mass quality in the ore column (quantified using Laubscher's Rockmass Rating, or MRMR) and drawpoint spacing. He argues that dilution entry (and hence recovery) depends on the HIZ, column height, swell factor, and the degree of uniformity with which draw is executed. Based on sand experiments, Laubscher (1994) also establishes a maximum ratio for drawpoint spacing based on the IMZ (or Isolated Draw Zone, IDZ, as defined by Laubscher 1994). According to the author, when draw zones are spaced at approximately 1.5 times the

IDZ diameter or less, interactive draw is likely to occur. This number has been very important for extraction level drawpoint design as it has guided the limit in drawpoint spacing to ensure interactive draw (Guest 2007; Trueman et al. 2008). Importantly, Laubscher builds a design abacus (Figure 2) that relates the expected fragmentation and loading width to establish the resulting IMZ and recommend a maximum drawpoint spacing based on the approximately 1.5 ratio rule and some limited observations at mine scale (Laubscher 1994, 2000). However, in the same 1994 paper, Laubscher states that there is no basis to affirm that the 1.5 ratio rule can be wholly applied to coarse material. He also affirms that low-friction material (such as coarse caved rock) could flow greater distances leading to wider draw zones, therefore enabling wider drawpoint spacings. Finally, Laubscher (1994) suggests that further three-dimensional physical and numerical models should be developed to understand interaction of coarse caved material across major apexes for groups of drawpoints.

After the sand experiments, several authors performed large-scale three-dimensional physical model experiments at the Julius Kruttschnitt Mineral Research Centre, using crushed ore (gravel) as the model media to better understand the flow mechanisms of caved rock, as suggested by Laubscher (Power 2004; Halim 2006; Castro 2006).

By using gravel as opposed to sand, the models can mimic the caved ore in terms of particle shape, particle size distribution, friction angle and, more importantly, the ability to generate arching (Halim 2006). Two different scales (1:30 and 1:100) were used to model the flow behaviour of coarse caved rock (scaled d_{50} = 0.7 m) for scaled heights of draw between 100 m and 330 m, after a thorough similitude analysis was performed.

Results as reported by Castro et al. (2007) and Trueman et al. (2008) showed that the main variables that affect the IMZ geometry are the extracted mass and the column height. Scaled results as reported by Castro (2006) indicate that the IMZ width reached 20 m at 50,000 tonnes, 27.5 m at 100,000 tonnes extracted, and 35 m for tonnage values above. These results differ significantly from those proposed by Laubscher (1994), who argued the maximum IMZ for coarse caved rock is approximately 13 m; however, they reflect Laubscher's suggestion in 1994 regarding the generation of wider draw zones when considering low-friction material similar to the caved ore. Also, findings from the large-scale physical model indicated that when the distance between drawpoints was such that the IMZ overlapped, mass flow could be induced. Otherwise, mass flow did not occur. This differs from the 1.5 ratio rule proposed by Laubscher.

All physical models have the limitation of not including the cave mechanisms and assuming a state of granular flow where fragments are free to flow from the beginning of extraction (Castro 2006; Guest 2007; Trueman et al. 2008). Thus, after the development of the large physical model, Castro developed a numerical cellular automata (CA) code to expand the results obtained and incorporate other cave and flow mechanisms (Castro et al. 2007; Castro et al. 2009). Castro and others continued the development of physical modelling to feed the CA rules and replicate the effect on flow of other mechanisms such as fines migration, preferential flow, cave propagation and rilling, and secondary fragmentation. These models were still gravel models but in significantly smaller scale (up to 1:200), which are still representative of the particle mechanics, as confirmed by similitude analyses, and are significantly cheaper and simpler to operate (Castro et al. 2018). All of these physical models have emulated low column heights (less than 330 m). Thus, to date, no physical model has aimed to replicate gravity flow in high columns.

Several authors in the 1990s and 2000s proposed drawpoint spacing determination methodologies based on the results from the sand physical modelling and current practices at that time (Julin 1992; Cavieres et al. 2005; Susaeta et al. 2008). Despite the lack of supporting data, the limitations posed by the author, and the later disproving experiments, the semi-empirical design rules postulated by Laubscher (1994, 2000) are the foremost methodology used to assess drawpoint spacing (Guest 2007; Chitombo 2010). Today, even when numerical modelling methodologies are used to assess recovery and dilution for different extraction layout configurations, spacing ranges are selected amongst those already proven by the industry or inside Laubscher's abacus ranges. These methods overestimate the HIZ and therefore underestimate the recovery achieved by a given spacing on a given rock mass, as supported by mine data (Castro et al. 2012; Garces et al. 2016; refer to Figure 3). Their current application and reference are the main limiting factors to modify today's drawpoint spacing limit practices. Furthermore, as expressed by Laubscher (1994), Castro (2006), and Trueman et al. (2008), column height is a key variable in drawzone geometry. Therefore, the experimental basis of these empirical methods is outdated, given current context and recent industry experience in mining column heights being much greater than those emulated in the sand and gravel experiments.

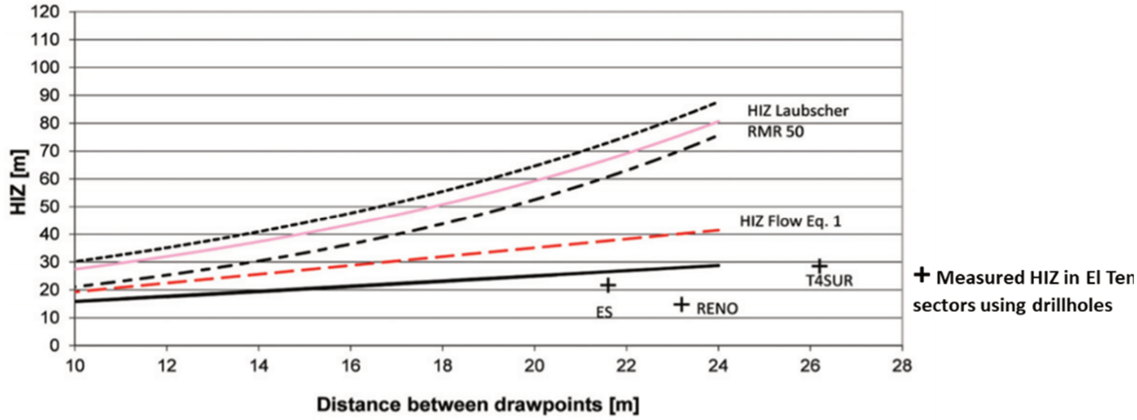


Figure 3 Measured HIZ versus estimated HIZ with Laubscher's Methodology (Garces et al. 2016)

2.2 Numerical modelling approach

Numerical codes that simulate gravity flow have been used since the 1990s to understand and predict gravity flow outcomes in block caving (Guest 2007). The numerical codes used to simulate gravity flow developed and used to date can be classified into two main categories: (1) Discrete Element Method (DEM), used to represent the physics of flow, and (2) Flow Emulators, used to emulate flow characteristics speeding up computation and allowing large numbers of drawpoints to be simulated (Hancock et al. 2010). Other numerical methods to assess ore flow outcomes are volumetric models, such as Heslop and Laubscher's model (Laubscher 1994, 2000). These volumetric models have been used to develop efficient tools for production scheduling as opposed to a means of understanding gravity flow mechanisms and the influence of different variables in these.

The DEM has been used as an alternative to physical modelling to understand flow behaviour and consists of dividing the media into discrete elements that replicate physical interactions of actual particles. In 1995, Guest & Cundall (1995) developed a DEM code called Particle Flow Code (PFC) to assess the effect on the gravity flow process when the physical characteristics of the material were varied. As the code was computationally expensive, only limited size, column height and particle distributions could be modelled in realistic timeframes (Guest 2007; Hancock et al. 2010). In order to solve the inherently slow nature of DEM, Lorig and Cundall (2000) developed a Rapid Emulator Based on PFC3D (REBOP).

Hancock and Weatherly (2008), Hancock et al. (2010), and Hancock et al. (2012) use the ESyS-Particle code, which is a supercomputer implementation of the DEM, to simulate gravity flow and compare the results to Pierce's PFC3D, and Power's and Castro's JKRMC physical model findings. Results obtained with the ESyS-Particle code reproduce those postulated by Castro and Pierce to a certain extent. However, they show flow dynamics to be more chaotic than that predicted by existing flow theories. Despite Hancock et al. (2010) postulating that the ESyS-Particle code could simulate large draw heights (above 500 m), no further work has been conducted to simulate flow at large heights.

2.2.1 Kinematic models

Kinematics is the study of particle motion regardless of the forces that cause it. The kinematic model for gravity flow was further developed by Nedderman (1995) for IMZ limits and internal velocities estimation after a certain mass has been drawn (Pierce 2010). The REBOP code developed by Lorig and Cundall (2000) is similar to the kinematic model proposed by Nedderman (1995) but is based on the generation and evolution of disk-shaped layers to generate the IMZ as opposed to functions fit to observed IMZ shapes (Pierce 2010). These layers grow based on rules derived from PFC3D findings, linked to drawn tonnages via mass and volume balances.

Pierce (2010) incorporated different gravity flow mechanisms into the REBOP code. Based on experimental and empirical evidence at the time, Pierce (2010) postulated that the key observed behaviours in gravity flow in block caving are: IMZ internal velocity and width distribution associated with an isolated flow zone as a result of draw and material characteristics; rilling when the IMZ intersects a stalled cave back or ground surface; IMZ overlap above multiple drawzones; stress-driven flow of stagnant zones prior to overlap; secondary fragmentation as a result of fragments breakage along the column; and fines migration causing preferential flow of finer particles.

Pierce (2010) adds all these observed behaviours (except for rilling) into the REBOP formulation from a collection of works including the results from PFC3D experiments, IMZ physical modelling by Marano (1980) and Castro (2006), secondary fragmentation and fines migration equations from Bridgewater et al. (1978) and Bridgewater et al. (2003), and Nedderman's kinematic model. Further development of the tool to include rilling is then undertaken and validated by Fuenzaliza et al. (2016) against actual flow outcomes of Henderson Mine (Figure 4).

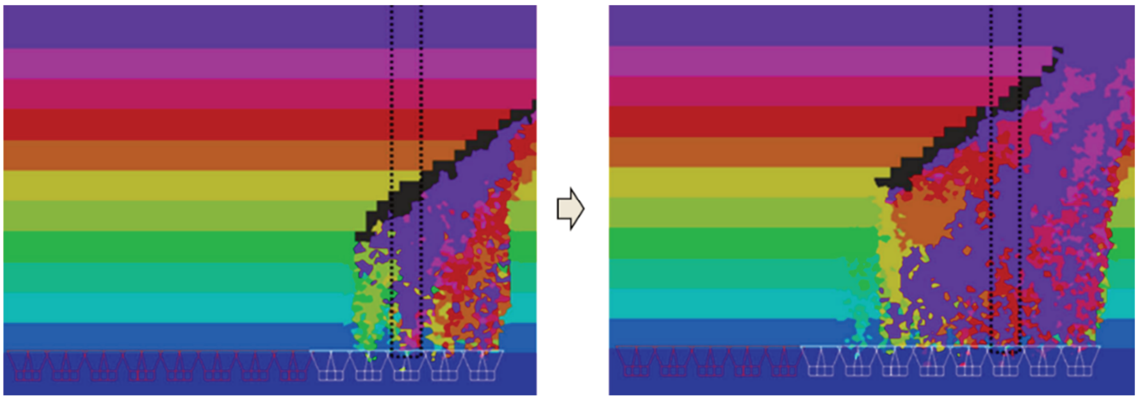


Figure 4 Cross-sections of drawpoints in REBOP showing particle migration due to rilling as drawpoint incorporation and draw progresses (after Fuenzalida et al. 2016)

REBOP is arguably the most developed kinematic model to assess gravity flow outcomes for block caving. It has been used by several authors to estimate draw zone shapes, recovery and dilution resulting from different extraction level layouts (e.g. Van As & Van Hout 2008; Vargas 2010; Castro et al. 2012). Also, studies have been conducted to calibrate and validate REBOP against actual mine data (Vargas 2010; Castro & Paredes 2012; Fuenzalida et al. 2016) which have shown the tool reproduces large scale gravity flow outcomes within acceptable limits for long term forecasting of macro sequences.

2.2.2 Cellular automata models

Cellular Automata (CA) models are stochastic models that include local rules (Castro et al. 2009). In the CA approach blocks will switch their position with ascending voids generated by drawpoint extraction. The ability to replace a void below will be subjected to probabilistic equations that emulate flow mechanisms, which parameters can be calibrated with results from physical models and/or empirical data.

Amongst the CA models, the most used codes to assess gravity flow outcomes under different conditions are CAVESIM, developed by Sharrock et al. (2004), and FlowSim, developed by Castro et al. (2009) (Hancock et al. 2010). Since their initial formulation, their authors have calibrated their parameters against available mine data and experimental evidence.

Castro et al. 2018 summarises the mechanisms that have been included in the code and the experimental background that supports it, including IMZ diameter evolution based on fragmentation, fines migration, cave propagation and its influence on preferential flow and rilling, and flowability affection as a result of the presence of fines, humidity and vertical load. Most recently, the latest version of the code is to include secondary fragmentation based on the model developed by Gomez et al. (2015).

Van As et al. (2011) use a CA model to hypothesise on the effects of high columns in recovery and dilution as compared to mining the orebody in consecutive shorter blocks. The authors outline the main risks for high column ore flow are (i) not achieving interactive draw, (ii) drawzone shrinking in height because of more secondary fragmentation compared to a low column causing excessive dilution, and (iii) vertical point loading from the high muck pile to be controlled with strict draw. However, the authors do not calibrate the models to actual high column mine data or evaluate the effect of wider spaced layouts.

2.2.3 Full scale marker trials

Over the last ten years few full-scale marker trial programmes have been implemented and analysed with the aim to better understand gravity flow in block cave mines. The three main programmes have been those implemented at Newcrest's Ridgeway Deeps (Brunton et al. 2012) and Cadia East PC1 (Brunton et al. 2016), and Codelco's Esmeralda sector in El Teniente Mine (Garces et al. 2016).

Garces et al. (2016) compared the marker data results to Laubscher's (1994) and found that Laubscher (1994) significantly underestimates the primary ore recovery compared to real data due to an overestimation of the HIZ (Figure 3).

Brunton et al. (2012) and Brunton et al. (2016) argue that marker recovery follows disturbed behaviour pattern as described by Sharrock & Hashim (2009). According to Sharrock and Hashim, in this disturbed mechanism, a wide fragmentation distribution can result in complex flow behaviours associated with internal arching, particle interlocking and fines percolation. Conclusions by Brunton et al. are mainly based on the near-field marker results, where flow can effectively be more influenced by particle interlocking and fines percolation as it approaches the drawbell and the zone of blasted material. Far-field marker (from 70 m above the extraction level) were not extensively analysed as they had not been all collected at that time. Further results from Cadia East PC1 markers have evidenced that rock fragments travel large horizontal distances (average 60 m and up to 150 m) for a 32 × 20 m El Teniente layout in the context of a high column cave.

2.3 Limiting factors for drawpoint spacing

Based on a critical literature review of the existing gravity flow models and drawpoint spacing determination methodologies, the following can be concluded:

Draw column height is a fundamental variable in gravity flow, and therefore recovery and dilution. Current methods to assess the relevant gravity flow outcomes of a given block cave layout (i.e. recovery and dilution) are based on physical experiments and empirical methods developed for low column heights, and their limitations have been evidenced with back-analysis of mine data, which have shown empirical methods to underestimate recovery by overestimating the HIZ.

The state-of-the-art methods in flow modelling that can be used to evaluate wider spacing for high columns are:

- Physical modelling with gravel in small scales (up to 1:200).
- Numerical modelling using Kinematic (e.g. REBOP) or Cellular Automata (e.g. FlowSim, CaveSim) models.

Current drawpoint spacing design practice is based on the same limits that were used in the early 2000s when empirical methods were developed. The effect of high columns in ore flow estimation and the overall recovery that can be obtained from wider-spaced drawpoints compared to current spacing practices has not been quantified to date. This constitutes the main limiting factor for the design and implementation of wider-spaced extraction level layouts. Therefore, further understanding of the effect of wider spacing in recovery for high column caves is required to support the implementation of wider-spaced layouts.

3 Evaluation of the effect of wider-spaced layouts in recovery for high column caves

In order to quantify the effect of wider spacing in recovery for high column caves, the following was performed:

- Back-analysis of the historical information from a high column block cave mine (Cadia East PC1), including extracted tonnages, grades, cave shapes interpretation, flow marker data and fragmentation. Cadia East Mine has been chosen as it is the world's highest column block cave mine established.
- Numerical modelling: Calibration and validation of numerical modelling tools (REBOP and FlowSim) using the information from PC1 to generate synthetic scenarios and quantify the recovery for different drawpoint spacing and column heights. The aim was to use both in order to cover the state-of-the-art of flow modelling. REBOP analysis was performed with assistance from Itasca to run the models. FlowSim analysis was performed with assistance from BCTec to run the models and generate post-processing data.
- Physical modelling: Two layouts (one representing current practice and one representing a wide-spaced layout) at different column heights (above 500 m high) to quantify the effect of drawpoint spacing and draw height in recovery, using the fragmentation curve from PC1. This was performed in the Block Caving Laboratory of the University of Chile.

3.1 Cadia East PC1 mine data

The Cadia East Mine is located 20 km south of Orange in New South Wales (NSW). It currently comprises PC1, PC2 and PC2-3 panel caves, the first two of which are in production. PC2-3 is currently in development as of June 2022.

The Cadia East lithology consists of Forest Reefs Volcanics, with a large monzonite porphyry intrusion, with RMR in the order of 60. There are several mine-scale faults associated with this intrusion. These faults include a number of sub-vertical east–west trending faults and thrust faults. Main principal in situ stress (σ_1) for PC1 (at 1,200 m depth) is approximately 63 MPa and for PC2 (at 1,400 m depth) 72 MPa.

The PC1 cave was established and propagated to surface from 1,200 m depth. The PC2 cave, located contiguous to PC1 but 200 m below, began its undercutting process after PC1. Thus, its cave propagation was significantly affected by the interaction with PC1 (Cuello & Newcombe 2018). Cave propagation is a relevant variable that affects gravity flow, thus given the complexity that the interaction process with PC1 cave generated in flow behaviour for PC2, only PC1 was considered for the analysis and calibration of the numerical modelling tools.

3.1.1 Cave establishment, propagation and historical draw

PC1 was established using a high (20 m) post undercut design with intensive preconditioning, between 2011 and 2014. Through the cave propagation stage, a cave monitoring array was used to generate regular interpretations of the cave back, which consisted of: a seismic system with accelerometers and geophones, open cave monitoring holes, a smart marker array, deep hole extensometers, survey prisms, and unmanned aerial vehicle flyover surveys.

Cave back surfaces were contrasted against the height of draw to determine a cave propagation ratio (cave back height/height of draw). The cave propagation ratio for PC1 varied throughout the propagation process, starting in an approximate average of 4 during the first 50 m of extraction and reaching an average of 8 for the remaining column height, with a maximum over 12 for some drawbells (Figure 5). Overall cave growth was rapid, forming a slender dome centred above the drawbells with higher extraction and then evolved into an expanding open cone on surface generating a waist at the top as extraction progressed (Figure 5). Both REBOP and FlowSim can constrain flow to caved volumes, therefore, the inclusion of cave back shapes is fundamental for the calibration of the tools to PC1 actual data.

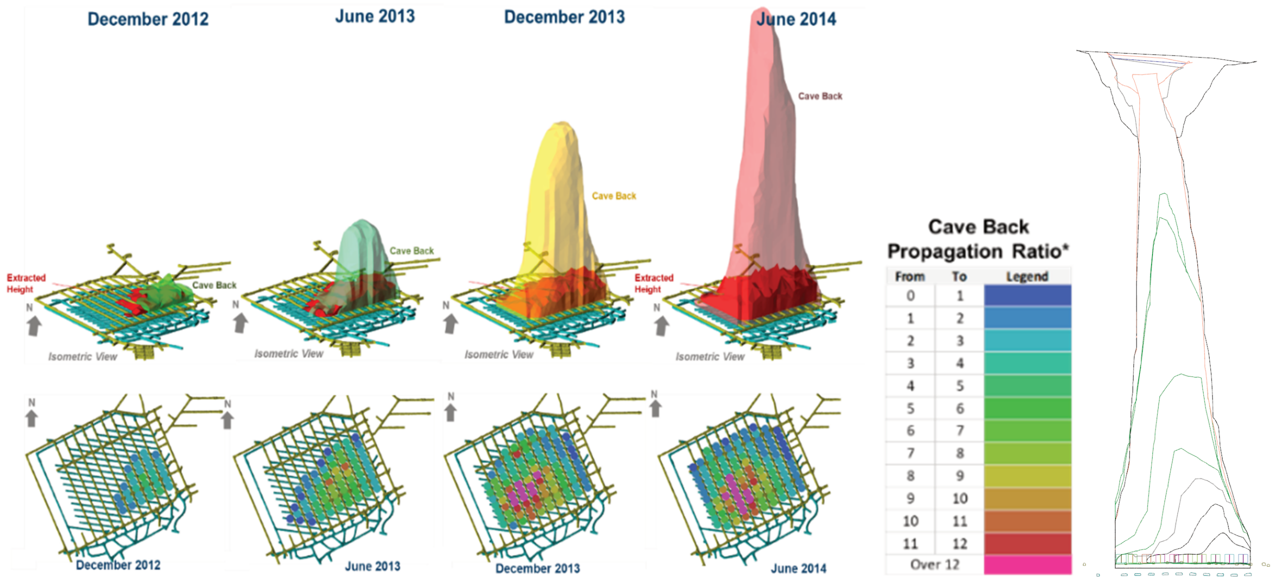


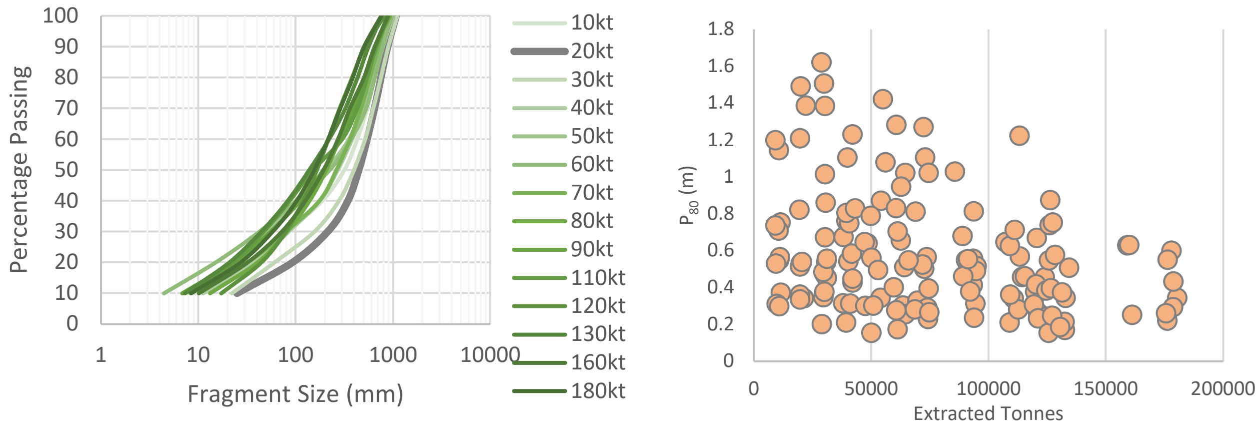
Figure 5 Left: Cave propagation ratio (cave back height/height of draw) plots for PC1, Right: PC1 cave back surfaces overlayed

Grades can act as tracers to understand the flow behaviour in a block cave column. The full historical draw and grades obtained from the life of PC1 were available to use in the calibration of the models.

3.1.2 Fragmentation and flow marker data

Fragmentation samples from PC1 were analysed by processing images in Split software (Itasca 2016). The database contains measurements for 70 of the 218 drawpoints in PC1 (32%) taken approximately every 10 kt of extraction. Fragment sizes observed in the drawpoints decrease as extraction evolves (Figure 6), as a result of the secondary fragmentation process occurring in the cave. Average characteristic diameter (P_{80}) for the primary fragmentation (20 kt of extraction, or ~20 m height of draw) is 0.8 m and decreases to 0.4 m at 180 kt of extraction (or ~200 m height of draw) (Figure 6). Variability in fragmentation between drawpoints decreases as extraction evolves, P_{80} for the first 120 kt (~140 m HoD) ranges between 0.1 m and 1.6 m (average 0.6 m), and between 0.1 m and 0.9 m (average 0.4 m) for extraction above 120 kt.

REBOP has a secondary fragmentation logic incorporated in the software that is based on the Bridgewater et al. (2003) attrition model, thus comparisons of actual to modelled fragmentation can be performed using this dataset to understand the ability of REBOP to reproduce actual flow after calibrated. The available version of FlowSim with which this work was conducted does not have a secondary fragmentation logic incorporated.

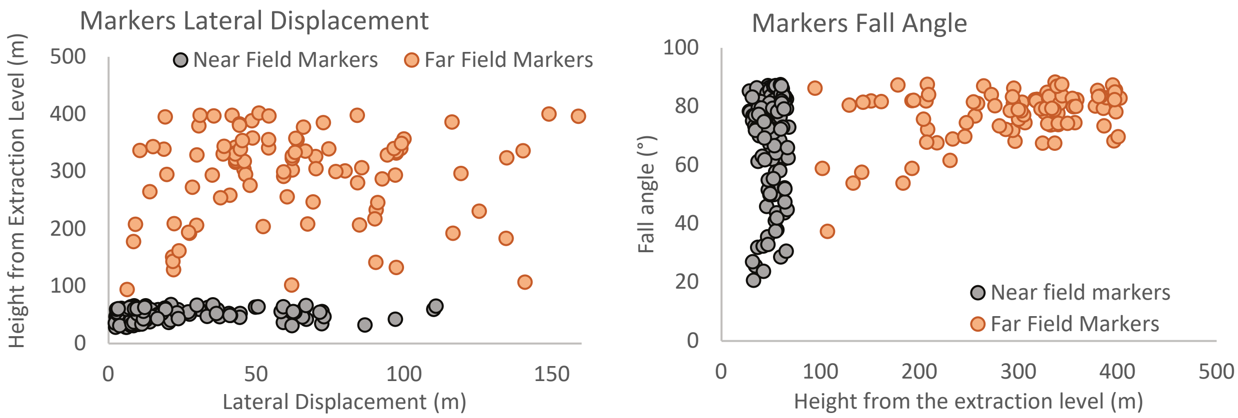


(a) (b)

Figure 6 (a) PC1 measured fragmentation average curves for different extracted tonnages; (b) Characteristic size (P_{80}) as a function of extraction, showing both size and variability decrease with extraction

Full-scale marker experiments were performed in PC1. Near-field markers were installed from the undercut level covering the extent of a drawbell. Far-field markers were installed in the engineering level (380 m above the undercut) and through drillholes below the engineering level to cover the height range. Both near- and far-field recovered markers evidence very large lateral displacements, up to 160 m, through PC1 footprint (Figure 7). The average lateral displacement for the far-field markers was 62 m ± 35 m, which significantly exceeds the influence diameter of a drawbell, indicating that the material did not migrate completely vertically.

An analysis of the fall angle shows that the majority of the far-field markers migrated downwards following an angle between 70° and 90° (Figure 7). Near-field markers migrated with shallower angles from approximately 30° (close to the angle of repose) up to 90°. Material in the cave can experience lateral migration due to differential draw and particle interaction (Susaeta et al. 2008; Sharrock & Hashim 2009; Castro & Paredes 2014; Paredes & Pineda 2014) and rilling along the cave boundary (DeWolfe 1981; Kvapil 2004; Castro & Paredes 2014; Paredes & Pineda 2014; Fuenzalida et al. 2016). Both internal movement and rilling are incorporated in the REBOP and FlowSim algorithms.



(a) (b)

Figure 7 (a) Markers lateral displacement; (b) Markers fall angle

3.2 Numerical modelling analysis

3.2.1 Cellular automata (Flowsim)

FlowSim has been previously calibrated to experimental physical modelling data to associate the primary fragmentation characteristic diameter (d_{80}) to the isolated extracted zone (IEZ) diameter (Castro et al. 2018). Physical experiments conducted by Castro 2006 indicate that for coarse material, IEZs can evolve up to 35 m diameter, this is generated in FlowSim with an input d_{80} of 1.2 m, which is in the range of the coarser part of PC1 fragmentation. Four different flow hypotheses (with IEZ's ranging between 12 m and 35 m) aiming to cover scenarios where flow was governed by the fine, medium or coarse fragmentation observed in PC1's columns were simulated. Results showed that FlowSim was able to replicate PC1 grade profile and error RMSE (root mean square error) grade errors at a monthly level, ranging from 7% to 26% for the different grade elements (near pre-feasibility study (PFS) level of accuracy). Lateral displacement observed with the PC1 markers (62 m average, 159 m maximum) was not fully replicated by the cases evaluated, the largest IEZ (35 m) showed the largest average (21 m) and maximum (91 m) total displacement. However, the IEZ = 35 m generated the lowest grade error and largest lateral displacements and replicated flow outcomes at a macro block level within a PFS level of accuracy, therefore it was used for the extrapolation to a generic block assessment.

The generic block assessment had the objective to quantify the effect of wider spacing layouts in recovery and interaction for high column caving, and determine if there is any associated fatal flaw. The main considerations for the analysis are summarised in Table 1. A footprint size of 100,000 m^2 was selected to represent a typical macro block size. A depth of 1,400 m with varying ore column heights from 500 m to 1,000 m were selected to represent the nominal depth and height of draw conditions encountered for deep caving projects (Figure 8). The ore column flow conditions (IEZ parameters and cave propagation ratio) were taken from the calibration to PC1 to represent those of a competent rock mass with intensive preconditioning. A weak waste (dilution) overburden was set on top of the ore to include the dilution fines migration phenomenon.

Table 1 Consideration for generic block analysis in FlowSim

Variable	Consideration
Block footprint size (m^2)	100,000
Block depth (m)	1,400
Column height (m)	500, 800, 1,000
Waste (dilution) overburden (m)	900, 600, 400
Ore column fragmentation	Coarse (IEZ = 35 m, calibrated from PC1 analysis)
Waste fragmentation	Fine (represented by d_{80} = 0.1 m)
Cave propagation ratio (m:m)	Below 50 m HoD: 1:4; above 50 m HoD: 1:8

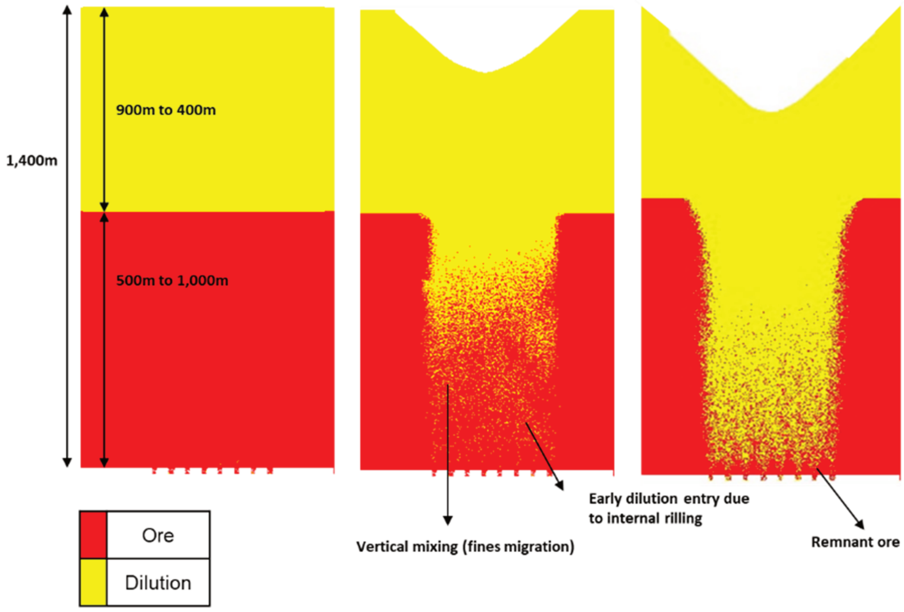


Figure 8 Schematic representations of flow considerations for FlowSim Generic Block Analysis

Five different layouts were tested to gradually understand the difference the drawbell area increments generate in recovery and interaction, these were:

- El Teniente 32 × 20 m: Cadia East nominal layout.
- El Teniente 34 × 24 m: 30% increase in area from Cadia East layout, and limit of current practice.
- El Teniente 38 × 25 m: 50% increase in area from Cadia East Layout, and outside current practice.
- Square 38 × 25 m: To understand the effect of Square vs El Teniente layout.
- Square 45 × 30 m: Approximately twice2 times the area of Cadia East layout, and approximately 33% reduction in extraction and drawbell drives development.

Drawbell geometry affects the flow in the initial part of the column, therefore, to keep the analysis ceteris paribus, all layouts used the Cadia East drawbell design. All scenarios used the same undercutting sequence (from NW to SE), with an equivalent undercutting rate of 4,000 m^2/month, and PC1's Drawpoint Production Rate Curve in t/m^2/d. Block ramp-up profiles for the five layouts were equivalent to PC1's ramp-up. Production schedules draw the tonnage equivalent to the full ore column for every drawpoint in each case.

Results showed that the overall recovery increases with height of draw (~2% from a 500 m to a 1,000 m column (Figure 9), and decreases with layout spacing, however the latter effect is not significant. A ~50% increase in drawbell area generates a slight decrease of ~1% in recovery for a 1,000 m column. Depending on the value distribution of the ore through the column, this can have different NPV effects. However, the ore loss effect is felt late in the life of the mine. Also, going from an El Teniente to a Square layout, with less development for the same spacing, generates no observable impact on recovery.

All the layouts generated overlapping (interactive) flow zones for the different heights of draw tested. The height of the stagnant zone, or height of interaction, is the height measured from the Extraction Level Floor at which the flow zones start to overlap. The conoid type volume generated below this height corresponds to ore that is not recovered. For the different layout spacing, the height of the stagnant zone varies between 44 m and 62 m (Figure 10). This means that going from a standard 32 × 20 m to a 45 × 30 m (~twice the drawbell area) results in a ~18 m difference in heigh of interaction. This height difference contrasted against a 1,000 m column and is practically immaterial in terms of volume (~0.6%).

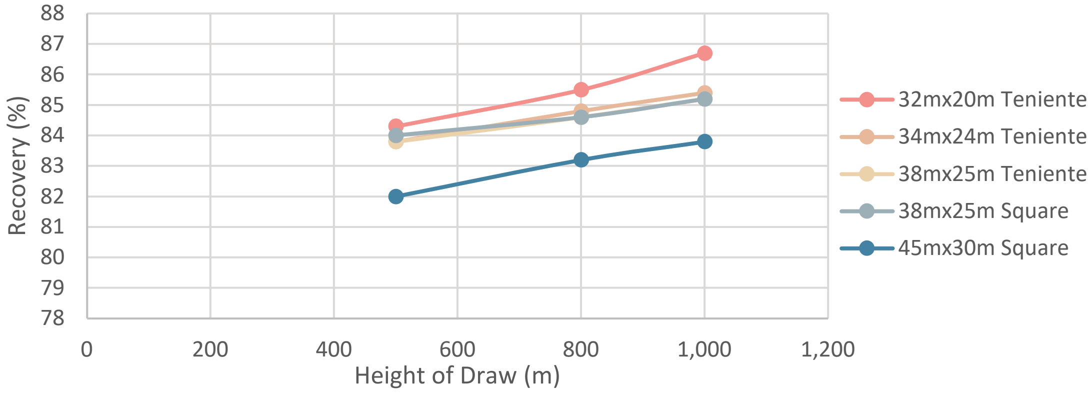


Figure 9 Recovery as a function of height of draw for different layouts

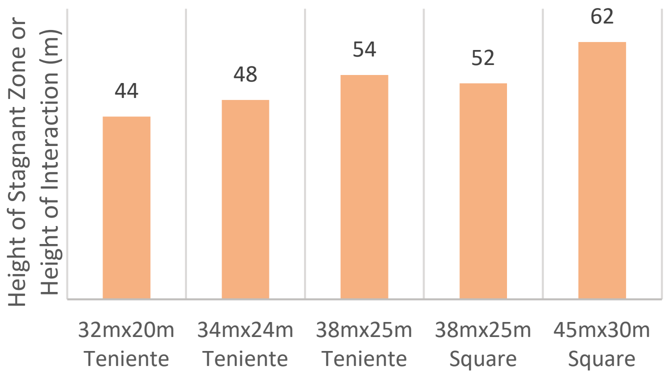


Figure 10 Height of stagnant zone (or height of interaction) for different layouts

3.2.2 Kinematic (REBOP)

Calibration and validation against PC1 was based on a critical review of the work performed by Fuenzalida and Ghazvinian (2021). Inputs for all flow mechanisms in REBOP were directly associated with measurable physical variables from PC1. This is a major difference between the kinematic and cellular automata approach, as the latter uses probability rules to replicate flow mechanisms observed in experiments which have input parameters that are not directly taken from physical variables that can be directly measured.

Considering the results from the calibration and validation, it was concluded that REBOP, calibrated directly to physical parameters from PC1, could reproduce the gravity flow process at a macro block level, this is based on the fact that the tool:

- Reproduced the extracted monthly grade profile for all the grades with a low error (normalised RMSE) of 7–8% for the different grade elements. This is significantly better than the errors obtained from FlowSim.
- Reproduced the secondary fragmentation process with errors from ~11–20% which is considered low, as it is below a PFS level of accuracy (+/- 25%) and closer to a feasibility study (FS) level of accuracy (+/- 15%).
- Reproduced the lateral displacement of material via the mechanism of rilling along the cave boundary for markers above 240 m, which is evidenced by markers with lateral displacements up to 120 m. However, it did not reproduce the lateral displacement for markers below 240 m or the maximum displacement of 160 m observed in the field markers. This may be due to the inherent limitation of having discrete stages of the cave back (monthly) in the simulation, which limits the amount of material that can rill along the cave boundary. Nevertheless, it does not have a significant influence on the overall macro block flow, as evidenced by the low monthly grade errors.

Considering the abovementioned, the set of parameters used in the calibration by Fuenzalida and Ghazvinian were used in the extrapolated generic block analysis as they represent the flow parameters from a deep cave mine with high columns.

A generic block assessment equivalent to the one performed with FlowSim was conducted with REBOP using the same overall considerations in terms of footprint and block geometries. The ore column flow conditions (REBOP input parameters and cave propagation ratio) were taken from the calibration to PC1 to represent those of a competent rock mass with intensive preconditioning. A weak waste (dilution) overburden was set on top of the ore to include the dilution fines migration phenomenon, the properties used for this were those calibrated from the Ca-La units from PC1, with a 5% maximum porosity and 30° friction angle to represent a weak material. Table 2 summarises the inputs used for the REBOP generic block assessment.

Table 2 Consideration for Generic Block Analysis in REBOP

Variable	**Consideration**		
Block footprint size (m^2)	100,000		
Block depth (m)	1,400		
Column height (m)	500, 800, 1,000		
Cave propagation ratio (m:m)	Below 50 m HoD: 1:4; Above 50 m HoD: 1:8		
Material properties	**Unit**	**Ore**	**Waste**
Solid density	t/m^3	2.78	2.7
In situ porosity	%	0%	0%
Maximum porosity	%	12%	5%
Friction angle	°	42	30
Primary fragmentation Weibull Distribution Parameter Alpha	–	0.86	0.56
Primary fragmentation Weibull Distribution Parameter Beta	–	0.45	0.042
Tensile strength Weibull Distribution Parameter Alpha	–	2.5	1
Tensile strength Weibull Distribution Parameter Beta	–	7	4

The same five layouts, drawbell design, undercutting sequence and rate and draw schedule considerations from the FlowSim analysis were tested in REBOP to gradually understand the difference the drawbell area increments generate in recovery and interaction. Results showed that, as in the FlowSim analysis, overall recovery increases with height of draw (~4% from 500 m to 1,000 m column (Figure 11)), and decreases with layout spacing. However the latter effect is not significant. A ~50% increase in drawbell area generates a slight decrease of ~0.5% in recovery for a 1,000 m column. Depending on the value distribution of the ore through the column, this can have different NPV effects. However, the ore loss effect is felt late in the life of the mine.

All the layouts generated overlapping (interactive) flow zones for the different heights of draw tested. For the different layout spacing, the height of the stagnant zone varies between 42 and 59 m (Figure 12). This means that going from a standard 32 × 20 m to a 45 × 30 m (~twice the drawbell area) results in a ~17 m difference in height of interaction. This height difference contrasted against a 1,000 m column is practically immaterial in terms of volume (~0.6%).

The difference between the recovery percentages band observed with REBOP (87–94%) as compared to FlowSim (82–87%) are mainly driven by the fact that the input parameters for FlowSim generate flow zones of approximately 35 m in width, whereas REBOP inputs (from PC1 data) generate wider flow zones above 40 m in width. This provides a theoretical range for the potential overall recovery results for a competent rock mass with intensive preconditioning and column heights between 500 m and 1,000 m. Importantly, for the main purpose of the analysis, the relative differences observed for the different layouts at different column heights in REBOP and FlowSim are consistent.

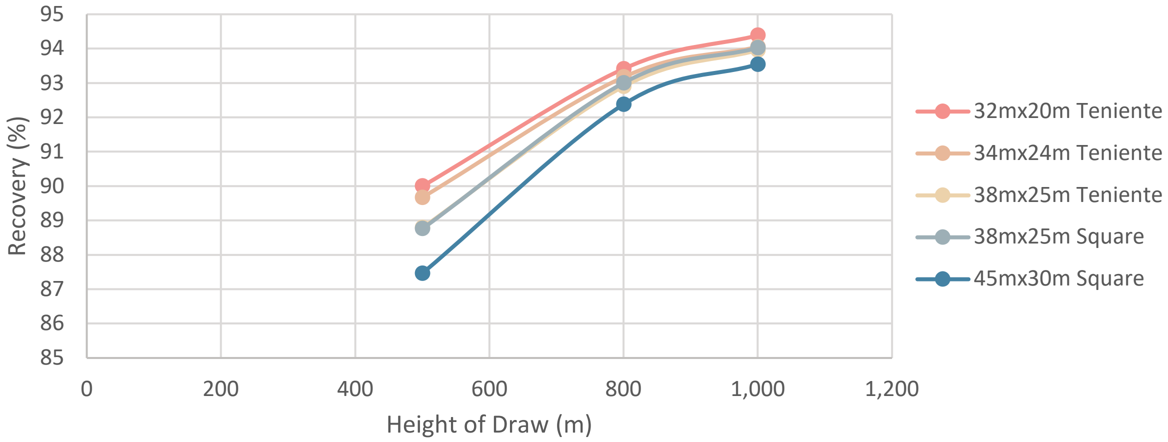
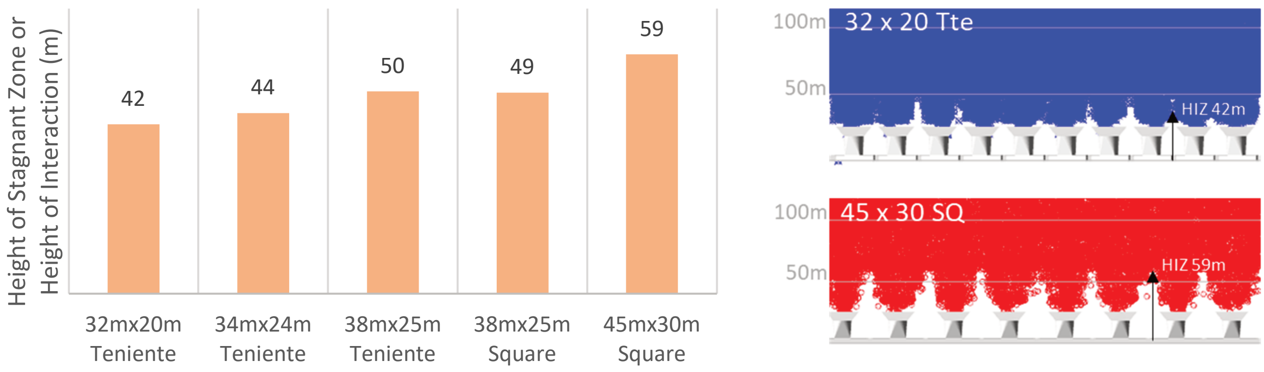


Figure 11 Recovery as a function of height of draw for different layouts



(a) (b)

Figure 12 (a) Height of stagnant zone (or height of interaction) for different layouts; (b) Cross-sections illustrating the difference between the height of interaction (HIZ) for a 32 × 20 m and a 45 × 30 m layout

3.3 Physical modelling analysis

The objective of the analysis was to conduct a physical modelling experimental program to quantify the effect on interaction and recovery of wider-spaced layouts for high columns and determine if any fatal flaws. The aim was to test two layouts: one representing current practice and one representing a wide-spaced layout at different column heights.

3.3.1 Experimental methodology

The experiments were implemented on a large pseudo 3D physical model made of steel and plexiglass so that the flow behaviour could be observed. The scale used for modelling was 1:200 using gravel, which was selected as it would allow large columns to be emulated at a scale were the material is still representative of the particle mechanics, as confirmed by similitude analyses published by Castro et al. (2018).

The dimensions of the physical model are shown in Table 3. Due to physical limitations of the model, the maximum column height that could be emulated at a 1:200 scale was 600 m. Thus, 300 m and 600 m were selected as the heights to be tested.

Table 3 Physical model dimensions

Dimensions	Experimental scale (cm)	Mine scale (m)
Length	150	300
Height	300	600
Width	32 (32 × 20 m El Teniente layout) 42 (42 × 24 m square layout)	64 (32 × 20 m El Teniente layout) 84 (42 × 24 m square layout)

Figure 13 (2) shows the model loaded with granular material. The extraction was controlled using a mechanised system with a servomotor for each production drive that allowed a uniform extraction in all drawpoints (Figure 13.3).

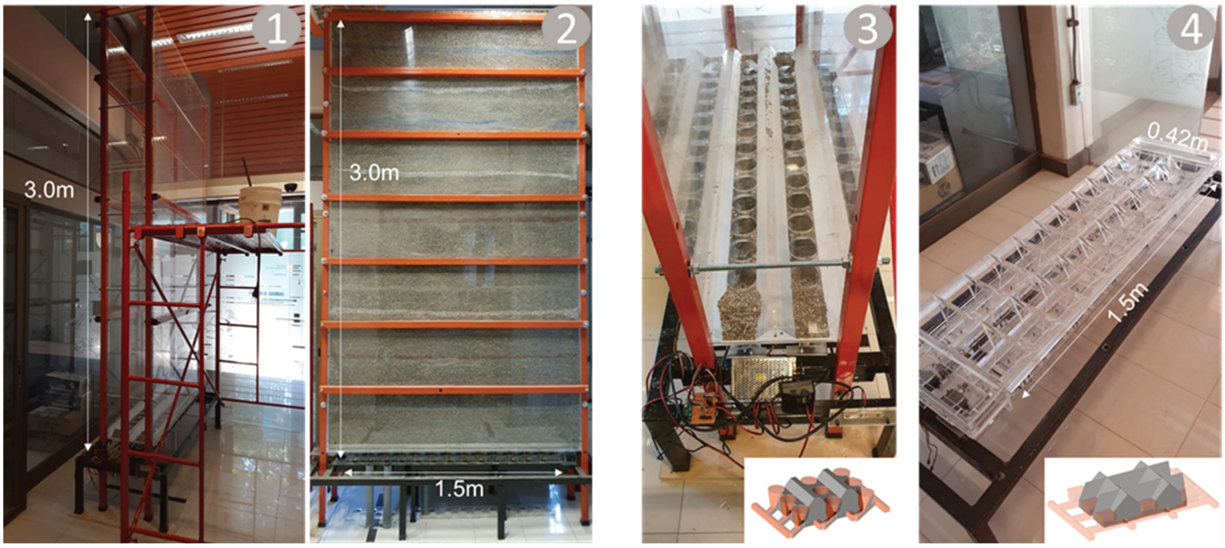


Figure 13 1: Model dimensions, 2: Model fully loaded previous to an experiment, 3: Model basis with 32 × 20 El Teniente layout and extraction system motors, 4: Model basis with 42 × 24 squared undercut-less layout

The two extraction level layouts tested are described below.

El Teniente 32 × 20 m^2 layout using Cadia East's circular drawbell geometry (Figure 14). This was selected to represent the base case for current practice. For this layout, 52 drawpoints were fitted into the model base (Figure 13.3).

Square 42 × 24 m^2 layout with a rectangular (undercut-less type) drawbell (Figure 14). This was selected to represent an alternative wider-spaced layout that also enables the elimination of the undercut level. For this layout, 44 drawpoints were fitted into the model (Figure 13.4).

The extraction zones were defined by the initial position of the markers extracted by each drawpoint. Marker layers were installed every 2.5 cm in height (5 m at mine scale) until 15 cm, then gradually incrementing the offset until 40 cm, and then every 20 cm until the top of the ore column. At each elevation, horizontal regular marker arrays were installed covering every 2.5 cm (5 m at mine scale) along the extraction drive direction and 4 cm (8 m at mine scale) perpendicular to the extraction drive direction for the 32 × 20 m layout, and 5 cm and 5.25 cm for the 42 × 24 m layout, respectively. The idea was to generate a higher density marker array for the smaller layout, which requires a better resolution due to size, but balancing the practicality of marker installation time.

The model media consisted of crushed granular material obtained from a local quarry from which different fragment size distributions were found. PC1 primary fragmentation curve was emulated for the ore component. Dilution was modelled using a fine material. Table 4 shows the main characteristics of the different model media.

Three experiments were conducted to quantify the impact of a wide spaced layout in a high column block, as summarised in Table 5.

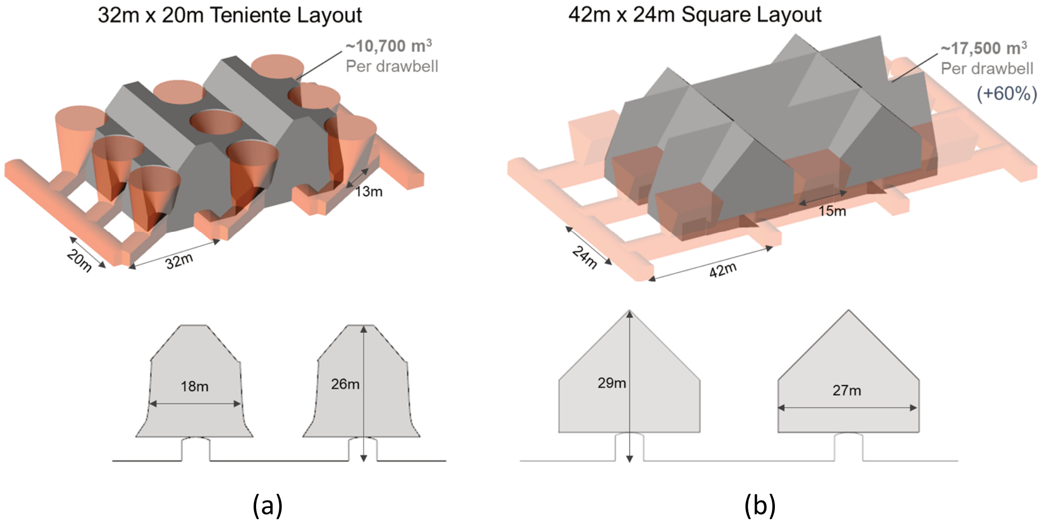


Figure 14 **(a) 32 × 20 El Teniente layout with Cadia East Circular Drawbell; (b) 42 × 24 m square layout with undercut-less type drawbell. Geometries and pillar shapes modelled**

Table 4 **Model media fragmentation**

	Mine scale			Experimental scale		
Size distribution	d_{20} (m)	d_{50} (m)	d_{80} (m)	d_{20} (cm)	d_{50} (cm)	d_{80} (cm)
Ore (coarse)	0.1	0.4	0.8	0.045	0.22	0.375
Dilution (fine)	0.1	0.1	0.1	0.035	0.04	0.045

Table 5 **Experimental plan**

Experiment	Experimental conditions	Objectives
1	Layout: 32 × 20 m² Teniente Height of draw: 600 m	Establish a baseline for comparison to a lower column and wider spacing layout
2	Layout: 32 × 20 m² Teniente Height of draw: 300 m	Quantify the effect of column height in recovery and interaction
3	Layout: 42 × 24 m² square Height of draw: 600 m	Quantify the effect of layout spacing in recovery and interaction

3.3.2 *Experimental results*

Table 6 summarises the main findings of the experiments at a mine scale.

Table 6 Summary of experimental results at a mine scale

Parameter		Experiment 1	Experiment 2	Experiment 3
Layout (m^2)		32 × 20 TTE	32 × 20 TTE	42 × 24 SQ
Height of draw (m)		600	300	600
Recovery (%)		91	86	92
Height of interaction zone (m)		36 ± 5	37.7 ± 7	29 ± 5
Extraction zone width (m)		36	32	34
Lateral displacement	Average (m)	14	12	12
	Maximum (m)	100	56	72

Column height showed an impact in recovery. When going from a 300 m to a 600 m column, a 5% increase in recovery was observed. This is due to the below effects:

- The HIZ is virtually the same for both cases (36 ± 5 and 37.7 ± 7, Experiment 1 and 2 respectively), but the remnant ore below the HIZ represents a greater proportion of the ore for the lower column case.
- The dilution entry point occurs sooner for the lower column, given the dilution source is closer (Figure 15, left). Therefore, the accumulated dilution drawn when the extraction is completed is higher for the lower column case.

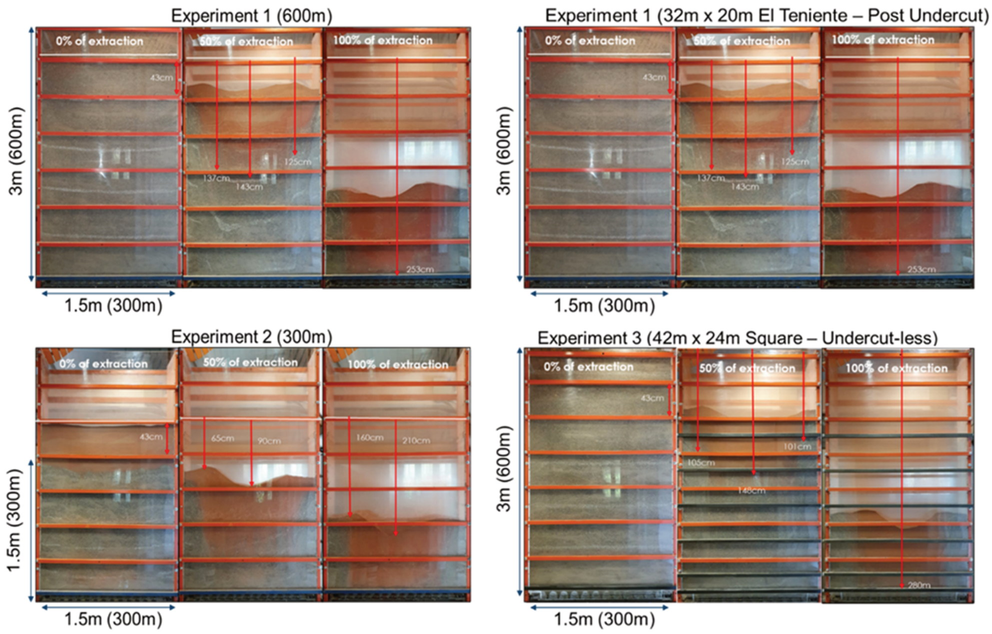


Figure 15 Left: Comparison of Experiment 1 (600 m column) and Experiment 2 (300 m column) extraction, Right: Comparison of Experiment 1 (32 × 20 m El Teniente) and Experiment 3 (42 × 24 m Square) extraction

Drawpoint spacing showed no material impact in recovery. When going from a 32 × 20 m El Teniente layout to a 42 × 24 m square layout, the maximum drawpoint spacing (in diagonal across the major pillar) goes from 25–36 m. However, the resulting recovery was virtually the same for both experiments, with the 42 × 24 m layout having a slightly higher recovery (92% versus 91%). This is because the HIZ for the widest layout is lower than the 32 × 20 m El Teniente. This can be explained by the difference in the drawbell-plus-undercut geometry. The El Teniente layout uses the Cadia East Post Undercut design which leaves a flat 5 m wide section on top of the major pillar, whereas the square layout uses an undercut-less type drawbell which leaves the top of the crown pillar with a sharp top (see Figure 14). This flat section of the post undercut design generates a stagnant zone on top, whereas the undercut-less design enables the material to flow directly into the walls of the drawbell. The plexiglass material plays a role in this phenomenon because its friction coefficient is lower than that of the flowing material. This is a limitation of the physical model in the near field. However, the flow in the far field is not affected by this.

The main limitation of the physical modelling approach is the inability to reproduce some of the relevant phenomena in high column flow. These are: cave propagation, rilling of material along the cave boundary, and secondary fragmentation process. That said, no fatal flaw in terms of interaction and recovery as a result of using a wider-spaced layout in a high column was identified from the physical modelling results.

4 Conclusion

Drawpoint spacing limit is a critical variable to enable the engineering of wider spaced layouts, which can reduce the amount of development to establish a block cave and improve the robustness of the pillars, ultimately leading to safer, faster and lower-cost establishment for deep and high column block caves. Column height is a critical variable in gravity flow which affects drawpoint spacing definition. However, since the 2000s, the drawpoint spacing ranges within the industry have remained unchanged despite the continuous increase in both depth and column heights of new block caving projects.

Current methods to assess the relevant gravity flow outcomes of a given block cave layout are based on physical experiments and empirical methods developed for low column heights. These represent the main limiting factor to implement wider-spaced layouts for high column caves. However, there has been significant progress in physical and numerical modelling of gravity flow, which can now be used to quantify recovery and interaction for high column caves using wider-spaced layouts.

State-of-the-art numerical and physical modelling, using calibrated data from a high column block cave that is representative of a competent rock mass with pre-conditioning (Cadia East PC1), was used to quantify the effect of wider spaced layouts in interaction and recovery for high column block caves. Results from the numerical and physical modelling conducted showed that:

- Recovery increases with column height. Numerical models showed an increase of ~2–4% when going from a 500 m to a 1,000 m column, and physical modelling showed an increase of ~5% going from a 300 m to a 600 m column.
- Recovery decreases with drawpoint spacing, however the effect is not significant overall for high columns. Numerical models showed that increasing the drawbell area by ~50% decreases overall recovery by 0.5% to 1% for a 1,000 m column. Depending on the value distribution of the ore through the column this can have different NPV effects; however, the ore loss effect is felt late in the life of the mine.
- Physical model results did not show a material difference in recovery between a 32 × 20 m El Teniente layout and a 42 × 24 m square layout when emulating the flow conditions of a competent rock mass with pre-conditoning in a high column context. This opens the possibility to explore options for application of layouts in between these spacing limits (e.g. 36 × 24 m) as a stepping stone towards the implementation of layouts with significantly wider spacing (40 m+) for these conditions. Further physical and numerical modelling can be performed to analyse these intermediate options in more detail.

- No fatal flaw in terms of interaction and recovery was observed for the conditions emulated based on the calibrated mine data. This data is representative of a competent rock mass with pre-conditioning. Therefore, conclusions derived from this work are not necessarily applicable to other conditions such as those of weak rock masses, which can generate narrower flow zones.

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