Cube Caving, a new cave mine design for the future

G. Dunstan
Director, Caveman Consulting Pty Ltd, Australia

ABSTRACT

Current Block and Panel caving designs are based on 40-year-old technology, the LHD, and as the future caving mines are deeper and in more challenging conditions (technical, financial, and social) a new approach is required. Advances in technology are providing opportunities, including computer modelling and simulation, wireless detonators, monitoring systems for seismicity and material movement (inside and outside the cave column) and trackless autonomous electric vehicles, not previously available to the caving industry.

The key design criteria identified to revolutionise the Block and Panel Cave layouts of the future are:

- Maximise the pillars to withstand the increased *in situ* stress conditions at depth via the creation of 90º intersections, eliminating angled drawpoints, and minimising the lateral excavation associated with equipment operation.
- Reduction in the total amount of development required to establish the caving footprint and the segregation of Cave Establishment activities, where possible. Leading to a reduction in the time required to undercut the footprint, resulting in a faster cave ramp up with improved metal production and cashflow.
- Acknowledgement of the variable fragmentation, and associated chaotic and disruptive flow, over the life of the drawbell. Starting coarse and becoming finer due to comminution effects, ensuring the drawbell design does not result in isolated draw columns in the later stages of the cave.
- Integrated drawbell and undercut design to ensure uninterrupted flow of cave material to the drawpoints, whilst maximising the effective width of the drawpoint to improve access to oversized material.
- Use of the airgap during cave establishment to assist with cave propagation and fragmentation, and
- Safety improvements through the drawbell and layout design which improves the operational management of water, fines, mud rush, vehicle and personnel interactions.

Operationally this new approach includes the segregation of loading and hauling functions to improve not only productivity but also the ore recovery through improved draw strategies.

1 INTRODUCTION

As deposit characteristics and ESG constraints are becoming more complex the mining of future mass underground operations is increasing in difficulty and uncertainty. The existing layout options for Block Caving are being extended beyond their technical limits with compromises being made between stability of the layout and cave material recovery, often resulting in significant financial penalties for the mining companies in either lost revenue,

increased footprint establishment costs or delayed production schedules which are leading to sub-optimal outcomes and reputational damage to the deep caving community.

Over the last 40 years there has been a shift in the deposits being excavated by caving methods. As the world economic situation changes and the desire for certain metals increases, e.g., copper and iron ore, the focus of transitioning some of the world's most productive Open Pits to high tonnage, bulk underground caves to extract their down dip extensions, continues. Adding to this many of the new large-scale deposits being discovered are deeper than previous deposits and many existing but undeveloped deposits are being re-evaluated as large-scale caving operations in a bid to make them economically viable.

As the deposits themselves are changing so too is the technology and mining philosophy available and/or required to successfully exploit them. Arguably, there are technologies and supporting systems available, and emerging, that provide the opportunity to revolutionise, rather than just evolve, how we mine (specifically using cave mining options) in the future, see Figure 1.

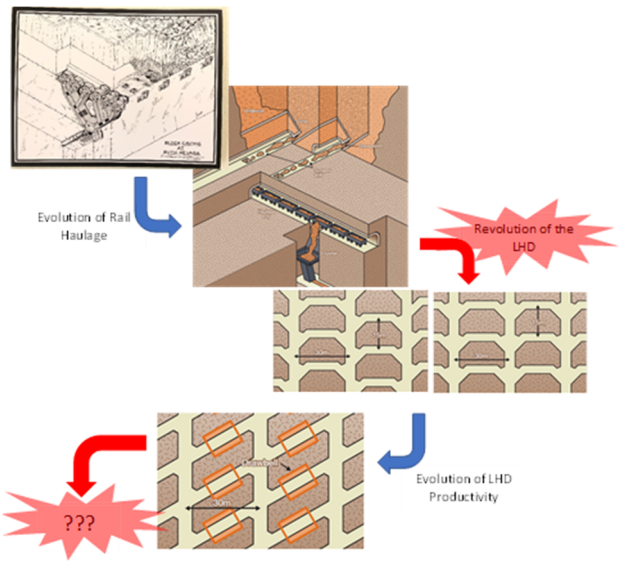

Figure 1 Block Cave layout progression.

The Block Caving mining method is comprised of 4 distinct stages, namely Development, Cave Establishment, Production and Closure. Each stage has specific requirements, and all are interlinked to ensure the overall success of the Extraction Level footprint.

1.1 Development

The development stage involves the lateral establishment of the target Extraction Level footprint and associated supporting infrastructure including the ventilation and materials handling systems. The development tolerances on the Extraction Level are to a higher level than in the rest of the mine, i.e., the declines and the Undercut level, as these are life of mine excavations in high stress environments. The quality of the development will have a direct influence on the long-term stability of the Extraction Level so considerable care needs to be taken to ensure the pillar cores and intersections have the best possible chance of remaining intact.

1.2 Cave Establishment

Cave Establishment can be defined as the combination of activities required to establish a cave (Block, Panel or SLC) mine. The activities which occur during this period include:

- Within the Orebody
  - Lateral development,
  - Undercutting,
  - Drawbell establishment,
  - Installation of temporary and permanent services,
  - Cave back monitoring,
  - Draw control and secondary break,
  - Pre and potentially Post Conditioning activities.
- Outside the Orebody
  - Infrastructure establishment including Crushers, Ventilation, Ore passes, Vertical hoisting (Shafts/Conveyors), Workshops, Offices, and meal rooms,
  - Operational Readiness which includes procedure development, operator and technical staff training and maintenance schedules for fixed and mobile equipment.

The Cave Establishment phase of a caving operation is the most critical period in the mine's life cycle as it is during this period where:

- the largest capital investment is made, on and off the footprint,
- the target ore block is undercut, and caving initiated, setting the future production profile and ore reserve recovery,
- the first commercial production and project payback commence,
- the *in situ* stress state surrounding the Extraction Level and associated infrastructure is changed significantly due to the establishment of the cave leading to potentially catastrophic stress releases in the mining area and long-term Extraction Level stability compromises,
- the rate of cave propagation determines the draw tonnages available against the size of the airgap forming between the cave back and the broken ore columns,
- technical management of the cave is crucial as you only get one go to get it right as retrospective corrections are often expensive and production inhibiting, both lead to significant negative financial impacts, and
- there are the highest levels of interaction between various disciplines, equipment and personnel leading to high levels of safety risk.

Fragmentation reporting to the drawpoint during the Cave Establishment period is particularly important as it directly influences the cave production. This is due to the impact it has on drawpoint availability, loader digging performance and the amount of oversize material which needs to be treated at the loader dump points (crusher bin or top of the ore pass(es)). The initial fragmentation reporting to the drawpoints is produced by the blasting of the drawbell and undercut material and is fine, it then coarsens up considerably as it changes to be material which has dislodged from the Cave back during the early stages of cave propagation (Figure 2). The effective drawpoint fragmentation then continues to get finer as the material travels further through the cave column and undergoes the effects of comminution.

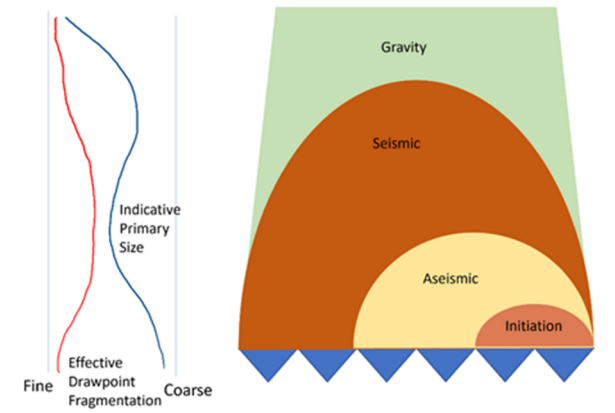

Figure 2 Fragmentation over time.

The mix of various activities during the cave establishment phase includes development, pre-production, construction and technical cave monitoring tasks. It is important to understand the interrelationships of these tasks and that they are all required to ensure a successful establishment of the cave. Experience indicates that a key enabler for all these activities to be completed as planned is to minimize the amount of congestion associated with multiple tasks being undertaken in the same area of the mine at the same time.

Technical monitoring and management during the cave establishment phase is paramount to ensure the minimization of catastrophic caving risks including cave stall, air blast, cave loading on pillars, stress bursting of pillars and floor heave. This requires the upfront installation and maintenance of monitoring equipment, data connectivity between the monitoring equipment and the technical and Short Interval Control (SIC) teams plus always allowing ease of access for technical personnel to the undercut and Extraction Levels.

1.3 Production

The production stage is usually defined as commencing when the cave has broken through to the level above or surface and all cave propagation restrictions have been lifted. During this stage the mine is looking to maximize the value of the material extracted whilst operating within the draw constraints to ensure caving

hazards such as convergence, fines, water, mud rushes, high seismicity and dilution are mitigated. Operational experience will target improved productivity and reduced costs during this period.

1.4 Closure

The closure stage is a complex time for the operation of an Extraction Level. This specific stage is when grade falls below economic limits in the drawpoints, and increased wear of the brows and tunnel convergence leads to reduced drawpoint availability. As the drawpoints are "turned off" the impacts on the surrounding drawpoints need to be considered to ensure that a stagnant drawpoint won't cause geotechnical issues to the still operational drawpoints around it. In many instances a low grade drawpoint may continue to be extracted from, with low tonnages, just to maintain the stress redistribution across neighboring drawpoints.

The technical monitoring and effort during the Closure stage is like that during the Cave Establishment phase. This is due to the requirements associated with successfully navigating the final stages of life in the cave column where cave loading, rehabilitation, water and fines management are as, if not more, important than the grade of the material being extracted.

The management of the activities required to successfully establish and operate a Block Cave is critical to achieving the mining company's objectives. With improvements in computing packages the mining team's ability to plan, schedule and execute the numerous interlinked activities is improving and the leading caving operations are continuously looking at additional ways to integrate this developing technology into their businesses. The opportunity to instantaneously adjust the mining execution plan based on live data enables faster reaction to plan interruptions whilst still making decisions aligned with the short-, medium- and long-term goals. This tactile software development also enhances the opportunity to implement autonomous operation, especially production loading, as it provides a better understanding of the operation of the footprint and the linkage, and prioritization, of tasks. This technology assistance is also being used to remove people from hazardous situations through monitoring and reporting on areas including, seismic activity, environmental conditions (air quality, heat, humidity) and convergence and ground support performance.

2 CURRENT LAYOUTS

The design of an Extraction Level in a Block or Panel cave involves the evaluation of several interlinked criteria, these are nominally (Arancibia, Carrasco, Fuentes, & Guarda, 2008):

- Stability
- Ore recovery
- Dilution management
- Productivity
- Materials handling system (MHS) restrictions

Current Extraction Level designs, namely the El Teniente and the Offset Herringbone, are based on two sided drawbells aligned to the primary stress field to minimize damage during cave establishment and the operating requirements of the production loading fleet. This approach has served the industry well for the last few decades though as the mines and new deposits get deeper with more challenging ground conditions, flaws in the design and trade off criteria are being exposed. The pillar geometry and associated development sequence of the Offset Herringbone has seen it lose favour as caving footprints have deepened as the El Teniente layout provides a more stable rectangular pillar with a simpler development approach.

The current drawbell layouts result in a series of stagnant zones between the mobilized extraction or flow zones. These stagnant zones are formed due to the blasting of additional rock to establish the drawbell and undercut geometry which compromises the *in situ* pillar capacity and ultimately results in the recompacting of cave material that generates additional vertical load onto the remaining *in situ* rock pillars further compromising the stability of the Extraction Level.

Accepted industry knowledge and simplistic sand model research, confirms that as material is extracted from a drawpoint the flow is initially somewhat elliptical and then beyond a certain point the width of draw no longer increases, apart from some small erosion effects. It is also accepted that as the draw zones from adjacent drawpoints interact, the combined draw zone increases and when all draw zones on the footprint are interacting this is called the Height of Interaction Zone (HIZ) (Laubscher, 94) above which point there is plug or uniform flow. The interaction of the draw zones also assists in redistributing the cave stress loads away from the Extraction Level. Ground conditions influence the draw zone dimensions with poorer ground conditions creating finer fragmentation and narrower draw columns requiring closer spaced drawpoints to achieve interaction, whilst good ground conditions create wider draw columns allowing larger drawpoint spacings.

The productivity rate of existing Block Cave footprints is limited by the following factors:

- Size of the tunnel which limits the size of the equipment,
- Tramming length from drawpoint to the dumping point,
- Number of Drawpoints available and their reliability,
- Fragmentation size, specifically the amount of material requiring secondary treatment,
- Number of potential production interruptions through the materials handling system from drawpoint to primary crusher,
- Draw strategy for the cave to maximise ore recovery.

2.1 Footprint Options

As the existing El Teniente layout is used in deeper and more challenging conditions, the operational impacts of utilizing an LHD to load material at the drawpoint and then tram it to a dumping point, ore pass or crusher, limits the production capacity of the level. With the limitations in the current layout of expanding the distance between the drawbells at the risk of inducing poor ore recovery through independent draw columns there is a finite limit to the maximum pillar size. The other option available to further increase the footprint pillars is to reduce the tunnel widths, though this has a direct impact on the size of equipment which can be operated safely within them. As the production loader size decreases the option available to maintain the desired productivity from a smaller capacity fleet is to reduce the tramming distance of the LHD which mostly rules out the ability to tip directly to a crusher (Figure 3), as any large excavations would need to be in stable ground outside the abutment zone. This results in the smaller capacity LHDs tipping to ore passes, either outside (Figure 4) or inside (Figure 5) the footprint or potentially a combination of both.

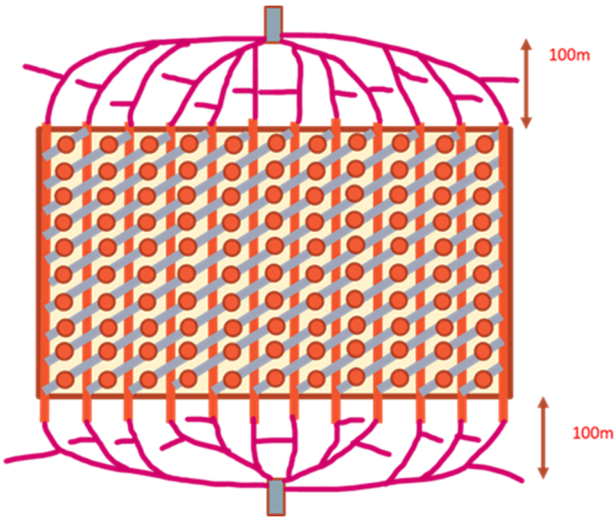

Figure 3 On footprint Crusher configuration.

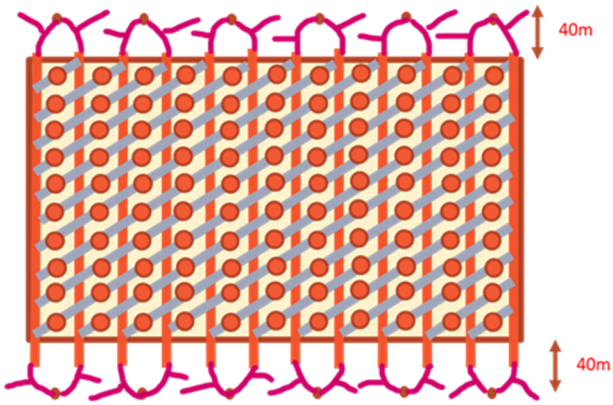

Figure 4 External Ore pass configuration.

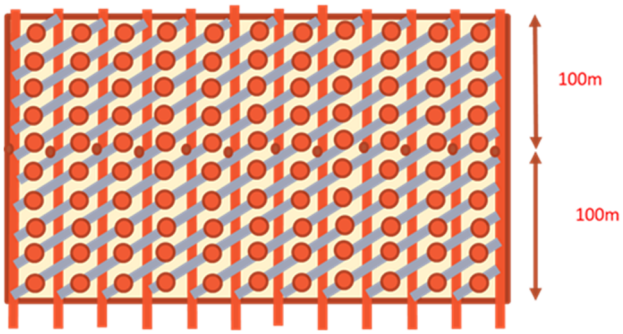

Figure 5 Inside footprint Ore pass configuration.

The constraint introduced by including ore passes in the materials handling stream is the maximum particle size which freely passes through the grizzly sizing bars on the top of the ore pass to mitigate the likelihood of hangups occurring in the ore pass. The result is the size of material required to pass through the ore passes is generally an order of magnitude smaller than the optimal sizing for a primary crusher, thus reducing its effectiveness. The use of ore passes also requires the inclusion of a haulage level to transport the material from the base of the ore passes to the primary crusher.

The other operational impact associated with the tramming length of the loaders is the draw strategy applied to the level. The desired approach is an even draw from all the drawpoints across the level in each period to maximise ore recovery, defer dilution entry and to ensure the redistribution of stresses within the cave column to limit the impacts of cave loading on the Extraction Level pillars. The productivity impact of this strategy is the longest tram determines the maximum productivity possible from the footprint.

Figure 6 shows a representation of a first principles analysis of the productivity expected from varying capacity loaders over a range of one-way haulage distances. If a productivity of 300tonnes per hour per loader is required, then the tramming distance needs to decrease from 360m for a 21t machine to 80m for a 10t loader. This is a >75% tramming route reduction for a 52% payload reduction which highlights that tramming length is more important than payload. Note that this analysis does not include any increases in non-productive time associated with operating smaller loaders in relatively coarser fragmentation conditions, it is purely based on equipment performance.

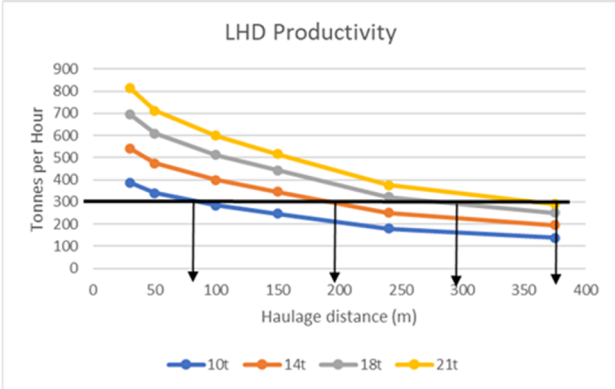

Figure 6 Loader Productivity by size and distance.

3 NEW DESIGN CONCEPT

A new layout, called Cube Caving, is proposed with a revolutionary 4-sided drawbell to improve pillar stability without compromising ore recovery. The design also reduces the time to establish the cave and increases the productivity per square metre of the footprint through the redefinition of the mobile haulage options on the Extraction Level.

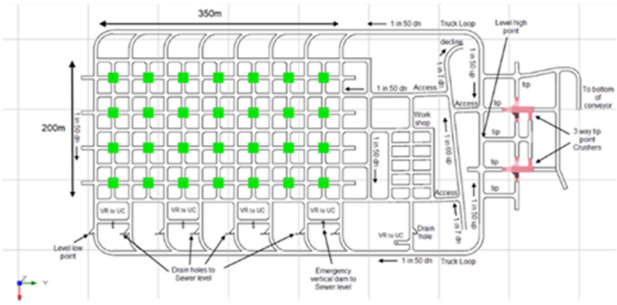

Figure 7 Plan view of the Cube Caving Extraction Level and MHS.

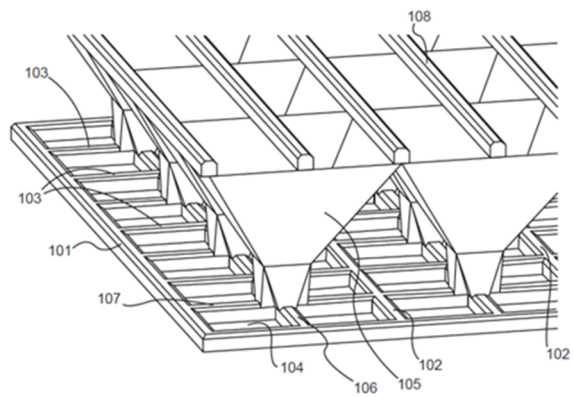

Figure 8 Isometric view of Cube Caving layout.

The proposed layout is comprised of a series of perpendicular Extraction and Drawpoint drives on 25m centerline spacing (Figure 7), all drives are 5m wide and the Drawbell drives are 5m high whilst the Extraction Drives within the footprint area are 6.5m high to allow 21t loaders to fill 65t haul trucks. The drawbells are centered at the intersection of the Drawpoint drives on a uniform 50m grid (Figure 8). The base of the drawbell is 12m across both intersecting drawpoint drives and 15m high. The Undercut Level is located 50m above the Extraction Level and has parallel drives on 25m centrelines. The undercut component of the drawbell is fired in a Post undercut sequence into the drawbell cavity in a series of blasts to manage the void ratio.

3.1 Undercut and Drawbell integration.

An important component of the long-term success of a Caving operation is the design of the drawbell to ensure that it enables uninterrupted flow of ore from the cave to the drawpoint over the life of the mine. The ultimate drawbell excavation is comprised of the integrated shapes of the drawbell established from the Extraction Level and the undercut shape formed from the blasting sequence on the Undercut Level. In the Cube Caving layout, the ultimate drawbell is 50m wide in both directions and aligns with its surrounding drawbells to ensure there are no flat spots or intrusions between the drawbells which will lead to rock ledges and pinch-points thereby interrupting the near and far -field flow of caved ore.

The multiple pass firings to shape the ultimate drawbell ensure that there is sufficient void available to accommodate the swell associated with blasting the subsequent firing. The ultimate volume of the new drawbell is approximately 36,000m^3 compared to an existing El Teniente drawbell at approximately 4,500m^3 or roughly 8 times as large, this additional volume within the drawbell is gained in parallel to improved stability of the footprint through the additional height between the Extraction Level and the Undercut Level.

The 90-degree drawpoints result in them being perpendicular to their associated topside of the drawbell which provides the maximum stimulation of the cave material from each load and minimizes the opportunities for flow interruptions through pinch-points. The integrated design (Figure 9) has the initial drawpoint from the Extraction Level fired high enough to create a suitable vertical brow to withstand wear during operation but one that is also low enough to create a greater than 50° slope out to the top of the drawbell to ensure that no cave material will sit on the slope and create hangups within the drawbell. These features ensure the drawbell design accommodates for the changes in fragmentation over the life of the cave.

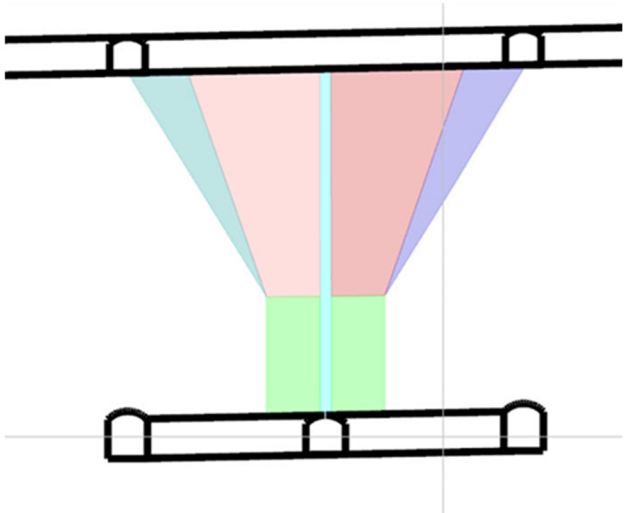

Figure 9 Drawbell and Undercut Firing sequence.

4 TECHNICAL ANALYSIS

The key technical considerations for any caving layout are the stability of the footprint and the recovery of the cave material. To understand how the Cube Caving layout compares to the existing industry dominant El Teniente layout Beck Engineering were engaged to undertake stability and flow modeling analysis, primarily due to their physics-based flow code, FS4, and how little code modification was required to model a 4-sided drawbell.

4.1 Stability Analysis

One of the industry standard modelling packages, Abaqus by Beck Engineering, was used to model the stability and cave loads on both footprint layouts. For the El Teniente design a 30m x 24m drawbell spacing was

selected for maximum stability as it was the largest 'contemporary' footprint design at the time.

4.1.1 Abaqus Inputs

A common location was selected within the Freeport DMLZ footprint for the two sub models, 16 Cube Caving drawbells and 35 El Teniente drawbells (Figure 10). The DMLZ Extraction Level is located at ~1350m and is below the exhausted DOZ mining block.

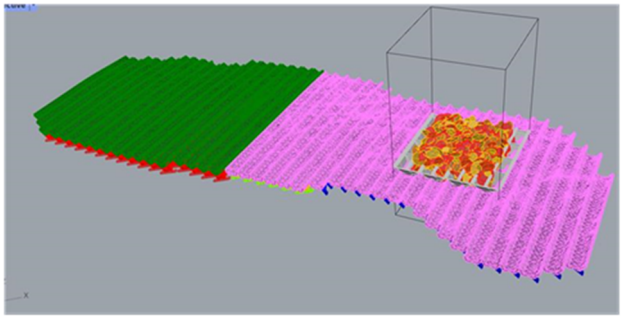

Figure 10 Sub model location within the DMLZ footprint.

For consistency both sub models used the same, explicitly built, Discrete Fracture Network (DFN) to remove any variability around rock type in the modelling, as shown in Figure 11. Two rock mass types were used in the models, Diorite, which is stronger and Endoskarn, which is a moderate strength rock.

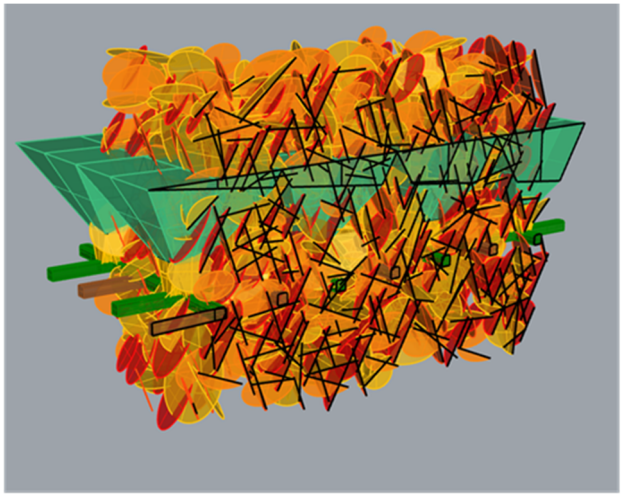

Figure 11 Discrete Fracture Network for the Cube Caving drawbell model.

Both sub models used the same mine establishment sequence derived from the original sequence in the mine's global model (Figure 12).

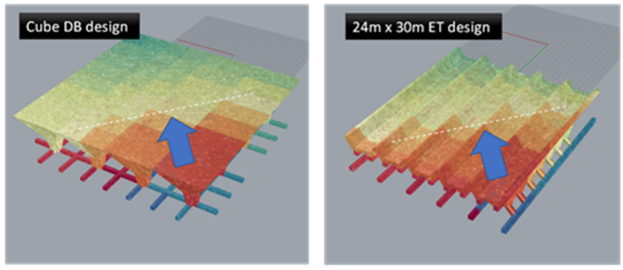

Figure 12 Sub model sequences for the Cube Caving and El Teniente layouts.

4.1.2 Measurement logic

All data was evaluated for the centre drawbell of the sub model to limit any boundary effects. Drive closure measurements were taken vertically and horizontally. The pillar stress was measured in a 27-point grid and averaged.

4.1.3 Results of Footprint Stability modelling

The Cube Caving design is forecast to experience significantly less closure in the drives and at the drawpoints than the wide spaced El Teniente layout. Drive closure estimates for the El Teniente layout were more than double the closure forecast for the Cube Caving design (Figure 13 and Figure 14). The behaviour is observed in both material types at each stage of production. When the cave loads are artificially increased at the end of mining to test stability effects the increase in loads has a marginal impact on the Cube Caving layout but a significant effect on the El Teniente layout, noting that the El Teniente layout tested has larger pillars than the typical 30m x 18m, used in the flow modeling simulations, or 30m x 20m layouts currently used in the industry.

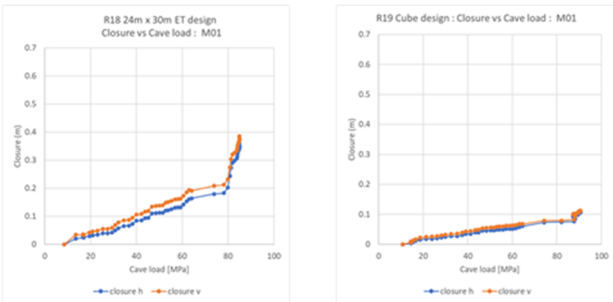

Figure 13 Drive closure comparisons for M01 Cave load.

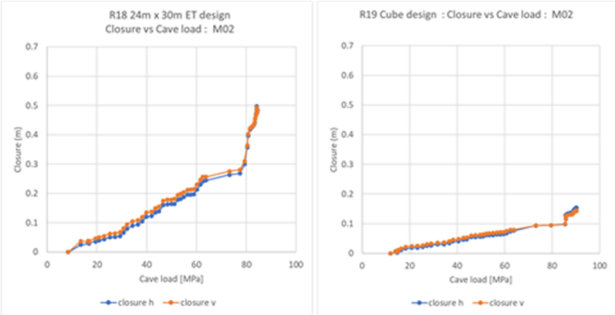

Figure 14 Drive closure comparisons for M02 Cave load.

Development in the Cube Caving design is subject to high levels of stress resulting in significant rock mass damage in the perimeter of the excavation that would require heavy ground support, though only minor levels of rock mass damage are forecast in the pillar cores, Figure 15 and Figure 17 (top). The drive closure estimates were well outside the risk parameters indicating that all drives and drawpoints are available for the life of the footprint.

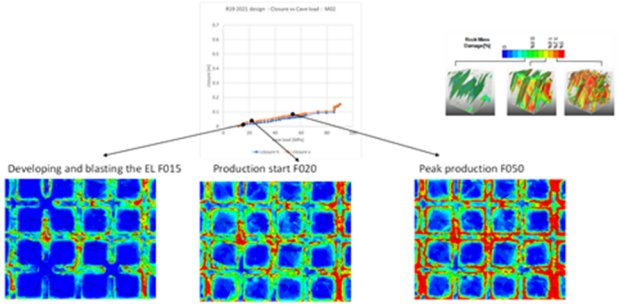

Figure 15 Cube Caving drive deformation over time.

In the El Teniente layout significant levels of rock mass damage extend through large portions of the pillars, Figure 16 and Figure 17 (bottom). The onset of rock mass yielding begins to occur in pillar cores as the cave loads increase leading to large scale Extraction Level instability. When a pillar fails its load is shed on to the surrounding pillars which can then lead to a domino effect of pillar failures and compromise sections of the Extraction Level.

Like the El Teniente layout the main vulnerability of the Cube Caving design is the 4-way intersections and the potential for deformation and damage of the drives in extreme operating environments. Relatively the Cube Caving intersections are more stable as they are at 90 degrees with consistent pillar geometry rather than the oblique intersections of the El Teniente layout.

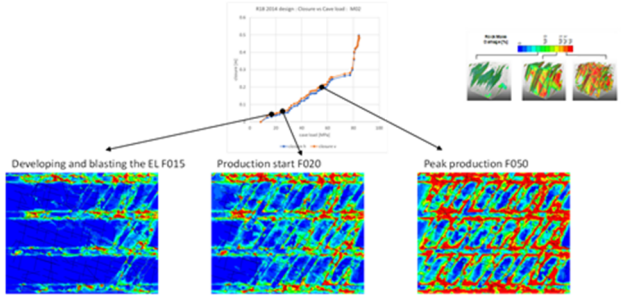

Figure 16 El Teniente drive deformation over time.

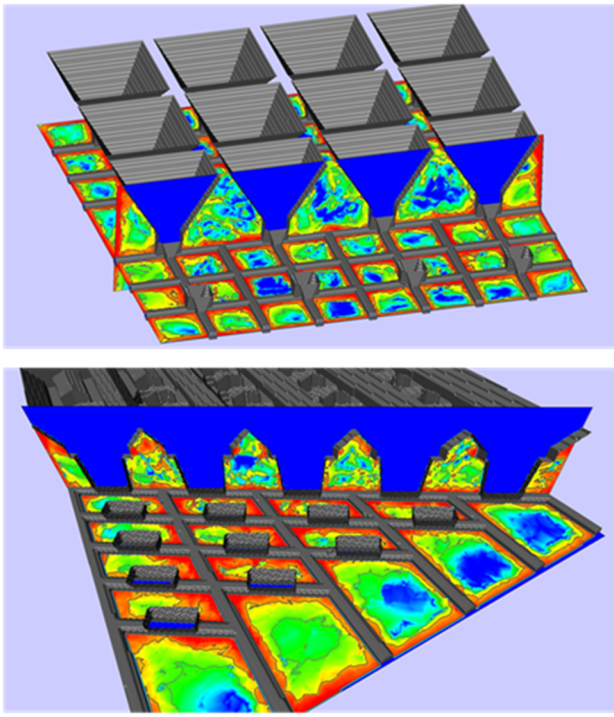

Figure 17 Comparison of rock mass damage for Cube Caving (top) and El Teniente (bottom) layouts.

4.2 Flow Analysis

Campbell (2020) stated that predicting material flow in caving mines is arguably one of the most complex tasks in rock mechanics with highly variable particle fragmentation, fines migration, particles interlocking and comminution occurring constantly through the drawdown of the caving muckpile. Additionally, there is the variability of rock masses within the caving column, the impacts of cave propagation including the number and magnitude of seismic events and the material extraction practices from the drawbells at the base of the columns.

After reviewing the computer simulation codes available to assess the flow in cave mining applications the Beck Engineering program, FS4, was selected. As FS4 is a new physics-based code the initial part of the flow simulation work was focused on replicating the results identified in the literature and early physical models to validate the code parameters and confirm the applicability of the new program.

Due to the scale of the model requirements the flow simulations were broken into 2 discrete models, a near field model and a far field model. The near field model was utilized to investigate the material flow performance and design impacts within 200m of the drawpoint. The far field model took the results from the near field model and extended the model height to >1,000m.

4.2.1 FS4 Inputs

The nature of flow and the resulting muckpile inside the cave, evolves from the constitutive properties of individual particles. Randomised draw was applied to the models to recreate realistic operational conditions. Drawpoints are drawn at small increments from a random number of drawbells in a randomized order throughout the model. The total draw tonnes for each bell were within ±5%.

The rock mass characteristics of Freeport's DMLZ mine were used in the model to estimate the flow and ore recovery of the Cube design and a comparative El Teniente 30 x 18m layout. Approximately 40 simulations were completed as part of the comparisons, covering single and multiple drawbell extraction regimes.

4.2.2 Flow model results.

The main findings of the single drawbell flow modelling were:

- The Extraction and Movement zones in the flow model forecasts are well matched to previous measurements in the literature and kinematic flow theory, (Figure 18)
- The movement zone height and width are significantly controlled by the lower drawbell geometry during early draw (Figure 19).
- The width of the Extraction zone for a single drawbell increases to almost 30m when all four drawpoints are in operation.
- The flow modeling of a 30 x 18m El Teniente drawbell demonstrated flow characteristics in line with the observations of Brunton (2016).

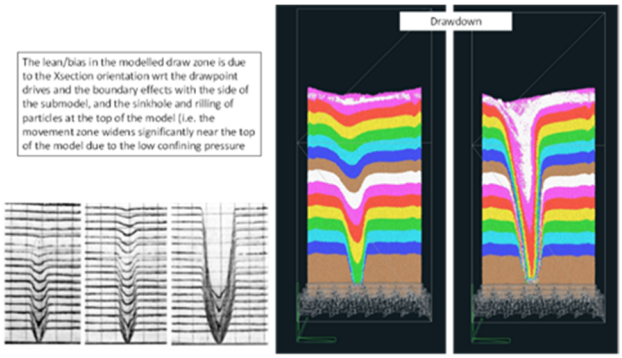

Figure 18 Movement zone comparison of sand models and FS4 simulations.

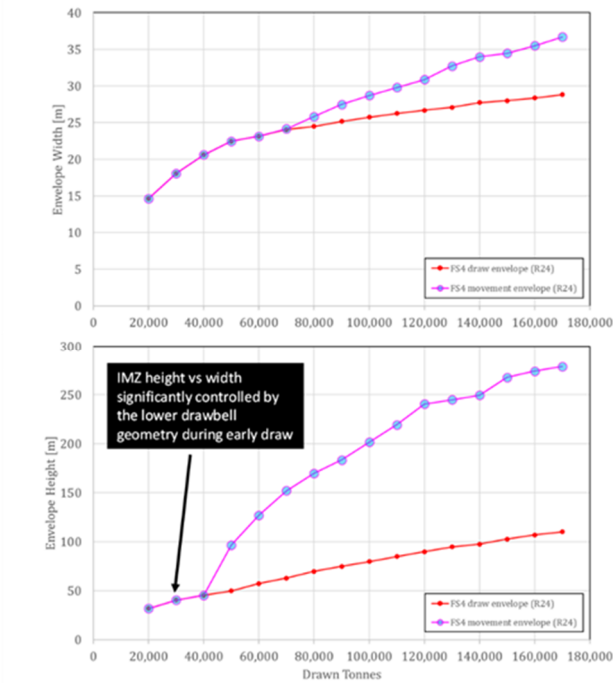

Figure 19 Drawbell geometry effects on the Movement Zone.

The main findings of the multiple drawbell flow simulations were:

- There is a low flow/dead zone area formed in the lower portion of the cave when two neighbouring drawbells are drawn,

(Figure 20 and Figure 21). The size of the low flow zone is similar for both incremental alternate draw as well as continuous flow simulations.

- Drawing from many drawbells with randomized draw patterns per mining period, to simulate real mining, results in a height of interaction and reduces the size of the low flow area between the drawbells. This height of interaction continues to diminish as the cave matures, mostly due to the progressive widening of the movement zones due to "erosion" effects.

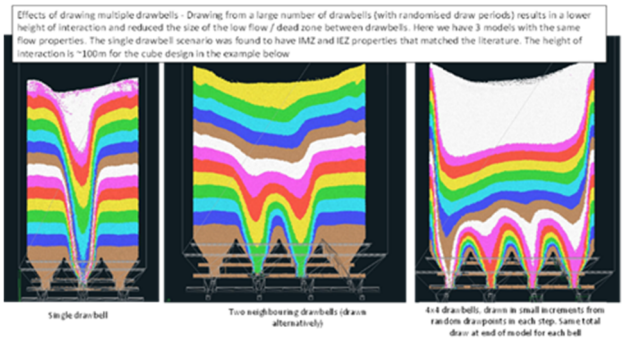

Figure 20 Low flow areas between drawbells.

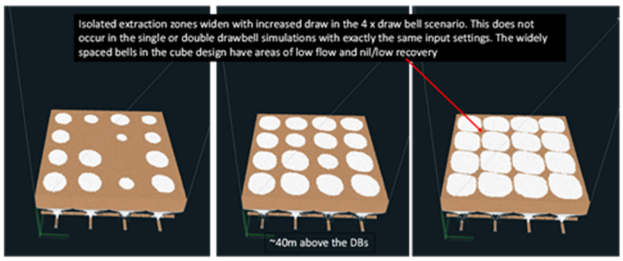

Figure 21 Progressive Extraction Zones for the Cube Caving layout.

As the FS4 flow simulator utilizes physics to determine the particle movements within the cave columns the results of the 16 (4 rows x 4 rows) drawbells are scalable and representative of the results which could be expected across a larger footprint. The location of the modelled drawbells was in the centre of the DMLZ footprint to remove any edge effects of the model space.

The flow performance of both layouts was similar when assuming uninterrupted access to the drawpoints in the preferred draw sequence.

4.3 Ore Recovery Estimates

The level stability of the Cube Caving layout results in fully available drawpoints with limited rehabilitation requirements and enables the execution of the preferred draw strategy across the footprint. Resulting in the full ore recovery estimates from the flow simulations being achieved.

The Extraction Level losses with the El Teniente layout result in deviations from the preferred draw plan and the high likelihood of ore losses due to access issues. The access issues lead to compounding operational impacts as static draw columns lead to additional cave load transfer on the Extraction Level pillars. As the timing of the drawpoint access issues, nor the compounding cave load issues, cannot be accurately forecast it is difficult to assess the likely impacts on ore recovery, rather a loss factor is the best that can be applied but it doesn't consider the operational or productivity impacts of losing a drawpoint or part of an Extraction Drive at various stages of the footprint life cycle.

The increasing amount of Extraction Level instability with depth and the inability of the El Teniente layout to accommodate the varying fragmentation through the life cycle of the Extraction Level makes forecasting the production rate and the total ore recovered over time very difficult. The current modelling approaches result in upper end performance expectations when reality is often lower.

5 MANAGEMENT AND OPERATING SYSTEMS

The Cube Caving layout offers several cave establishment and operational advantages to the current El Teniente layout. For comparison purposes a notional footprint of 350m x 200m has been used to compare the performance of both layouts.

5.1 Cave Establishment

Through the redesign of the Extraction Level to a series of parallel and crosscutting drives of consistent profile the level can be efficiently developed utilizing existing "long" round jumbos or rock cutting machines. The total

development metres are ~15% less for the Cube Caving layout compared to an El Teniente layout on a 32 x 22m spacing.

The larger pillars around the Extraction Level drives in the Cube Caving layout allows for the use of the more productive Post Undercutting sequence. Post undercutting enables checking of the drawbell shape post firing to ensure full breakage prior to firing the undercut into it. The larger void available for firing the undercut into allows for larger undercut firings, thus reducing the total number of firings required to establish the caving footprint by more than half. Additionally, all blasted material is directed to the Extraction Level which is set up for material movement as opposed to the Advanced Undercutting sequence, used in many caves to manage stress loads, where all blasted material from undercutting needs to be removed from the Undercut Level which is generally poorly set up for material removal as it is a temporary working area.

With most of the production drilling occurring on the Undercut level the Extraction Level is less congested. The 4-way intersections and length of the drawpoint drives provides a flexibility to allow drawbell establishment tasks to continue independently of each other creating a level of contingency not available in the El Teniente design.

The improvements in design and task scheduling lead to a significant increase in the production ramp up of the footprint. Comprehensive scheduling of the cave establishment activities indicates the possibility of opening the footprint at >10,000m^2/mth or roughly triple the industry average. This opening rate may not be possible due to the response of the rockmass to caving and the large redistribution of stresses involved. To overcome this an addition to the footprint development has been considered which involves blasting the lower 200m of the cave column (Figure 22) to provide pre broken material for the cave ramp up period and to also relocate any seismicity to >250m from the Extraction Level activities. This post condition blasting would also serve to reduce the fragmentation in the initial years of production thus ensuring a more reliable production performance.

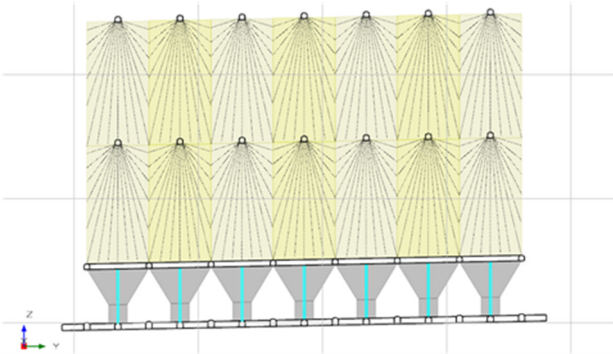

Figure 22 Long section showing drawbell, undercut and the two Post Conditioning levels.

5.2 Operational Performance

The order of magnitude improvement in the stability of the Extraction Level with the Cube Caving layout enables the excavation of larger Extraction Drive profiles. The increased profile facilitates the loading of trucks within the operating footprint which redefines the materials handling strategy on the Extraction Level.

The operational productivity of the Extraction Level is no longer defined by the tramming performance of the loaders and/or the fragment size that fits through an ore pass grizzly. The loaders now only travel a short distance, ~50m, from the drawpoint rill to load the truck at the intersection of the Extraction Drive. The trucks travel in a consistent direction through the Extraction Level, operating in expanding parallel loops, before then tipping directly to a primary crushing unit, located in a stable area off the footprint. The fragment size which now needs to be treated with secondary break is defined by the crusher, which for large gyratory crushers can be in the order of 4m^3, significantly reducing the amount of secondary break and clean up works in and around the Extraction Level.

A productivity assessment of the notional footprint was completed utilizing the ORB simulation package by Polymathian, Figure 23, which confirmed the performance expectations of the Cube Caving layout. A production target of 100,000tpd was achieved using 7 x 21t loaders working with 13 x 65t diesel trucks,

Table 1. If a higher productivity is required from the footprint, then additional loaders and trucks could be added as the cave footprint has excess capacity, though the bottleneck then becomes the primary crushing units.

From the authors industry experience and benchmarking, the Extraction Level production efficiency, Figure 24, of the Cube Caving layout is almost triple the industry average at 1.4t/m^2/day compared to ~0.5t/m^2/day. The most efficient El Teniente layouts of any size are 0.8-0.9t/m^2/day or roughly 60% of the Cube Caving layout.

Table 1 Cube Caving layout production simulation results

RESULTS SCENARIO ID	NETWORK LAYOUT	# OF LHDs	# of Trucks	Assumption Set	Tonnes per Day	Wait for Truck
1093	Proposed	7	10	Base	91,459	41.8
1123	Proposed	7	11	Base	95,877	29.4
1094	Proposed	7	12	Base	98,762	21.9
1124	Proposed	7	13	Base	100,685	18.2
1092	Proposed	7	14	Base	101,326	17.5
1125	Proposed	7	15	Base	102,724	14.6
1126	Proposed	7	16	Base	103,114	13.8

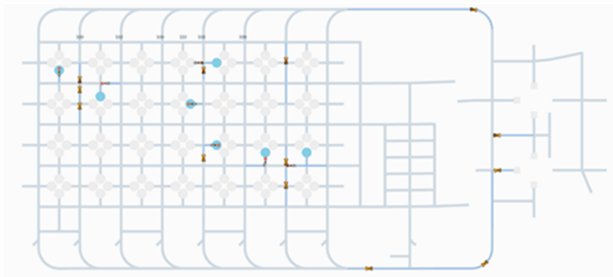

Figure 23 Screenshot of production simulation.

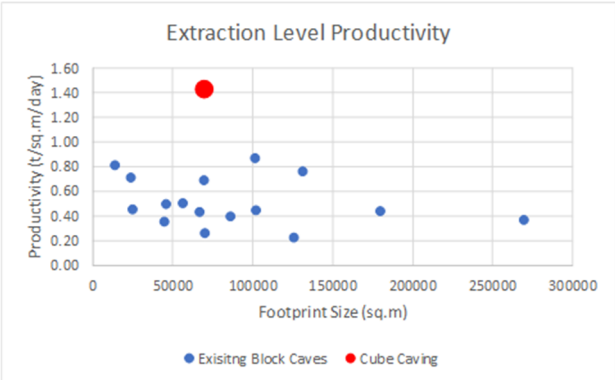

Figure 24 Extraction Level Productivity comparison.

The Cube Caving layout enables the loader or secondary break unit to fit entirely within the drawpoint drive and allows any other vehicles operating in the area to pass by. Each loader always has an alternate truck loading location should the primary location be unavailable due to a breakdown or rehabilitation activities.

5.3 Cost Estimates

5.3.1 Capital Cost Estimate

The capital cost to establish the Cube Caving layout is estimated to be within ±10% of a 32 x 22m El Teniente layout, though the establishment timeframe is approximately 30% less. This reduction in footprint development time leads to improvements in the financial metrics of the mine.

5.3.2 Operating Cost Estimate

The fleet efficiency of the Cube Caving layout leads to operating cost savings for the Extraction Level fleet as the equipment is utilized in the manner it was primarily designed, i.e. the trucks do the hauling, and the loaders do the digging. By reducing the loaded tramming distances and speeds for the loaders and straightening up the digging geometries the estimated maintenance costs for the loading fleet are considerably reduced. The secondary break fleet requirements are reduced in line with the reduced workload and the rehabilitation fleet requirements are almost eliminated.

The introduction of the trucks into the Extraction Level fleet is an operational cost increase compared to the mines running loaders directly to the crusher, though the reduction in loader numbers and efficiency of the truck fleet keep the estimated operating costs of the two within 10%. There are significant cost reductions, >40%, when comparing the Cube Caving layout to an ore pass and truck or rail haulage system as there are fewer operating components.

6 REAL WORLD COMPARISON

To challenge the theoretical advantages of the Cube Caving layout, a real-world assessment was completed by doing a comparison design for the BHP Carrapateena Block Cave. The Carrapateena BC footprint is at 1500m below surface, some 500m below the expected base of the existing SLC operation with rock temperatures expected to exceed 70ºC.

All off footprint infrastructure was kept consistent and only the active mining areas of the Extraction and Undercut levels were redesigned. The existing mine plan is to utilise a 32 x 22m El Teniente layout (Figure 25) and to extract the footprint in two parts, BC1 and BC2, with loaders direct tipping to a crusher located on the northern side of the footprint. BC1 is the larger and higher-grade footprint with a production rate of 12Mtpa, BC2 will commence approx. 6 years later against the side of BC1 at a reduced rate of 8Mtpa due to its location relative to the primary crusher.

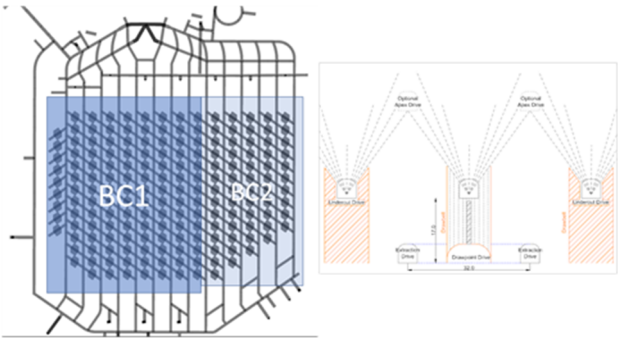

Figure 25 Carrapateena El Teniente layout and drawbell section.

6.1 Results

The mine plan for the entire footprint was redesigned with a 50 x 50m Cube Caving layout including the haulage loop, on level ventilation and dewatering circuits, Figure 26.

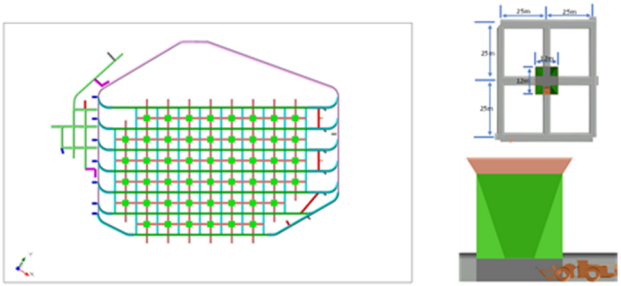

Figure 26 Carrapateena Cube Caving layout.

The ramp up duration from the first drawbell firing to the nameplate production was reduced from 44 to 21 months, though the existing mine plan ramp up is hindered by the installation of concrete roads and permanent services in the last 12 months of ramp up, see Figure 27. The Cube Caving layout was not impacted by these services installations as there were sufficient drawpoints and haulage routes available to maintain production while completing these tasks. The revenue associated with bringing the nameplate capacity forward was greater than the capital cost of the project.

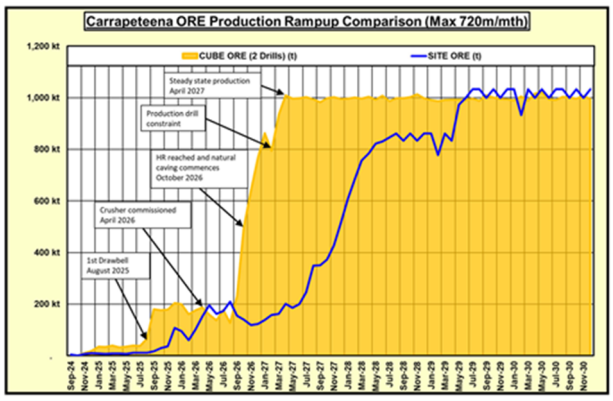

Figure 27 Ramp up schedule comparison for Carrapateena.

Due to the reduction in establishment cost and the ability for each drawbell to operate at the same production rate the entire footprint was established upfront with a consistent production rate of 12Mtpa achieved rather than 40% of the footprint being mined at the reduced 8Mtpa rate. These changes reduced the caving risk as the entire ore block was established at once rather in two sections 6 years apart though it did result in a slightly lower grade in the first 5 years as the material from the BC2 section of the footprint "diluted" the higher-grade material from the BC1 section.

The footprint establishment costs were reduced by 20%. The overall operating costs of the Cube layout were 40 to 60% lower than for the El Teniente LHD layout when using the high performance LHD parameters, this benefit would further increase should it be shown that the El Teniente LHDs were required to operate a reduced capacity due to the hot environment and therefore additional units were required to achieve the production targets.

7 CONCLUSIONS

The Cube Caving layout is a revolutionary design building on the knowledge gained through operating the existing El Teniente and Offset Herringbone layouts whilst being aware of their limitations. All equipment and resources

required to establish and operate a Cube Caving layout are already being utilised in the existing El Teniente layouts.

The comparison work completed on the Cube Caving layout shows:

- It is an order of magnitude **more stable** than a large spaced, 30m x 24m, El Teniente layout allowing larger Extraction Drives within the footprint without losing access to any drawbells,
- The flow simulations indicate that the recovery from the Cube Caving layout is comparable to a moderately spaced, 30 x 18m, El Teniente layout. The ore recovery estimates from the Cube Caving layout are therefore at **less risk** than the El Teniente layouts,
- Cave establishment rates are **significantly faster** through the segregation of tasks and schedule flexibility,
- Productivity from the Cube Caving layout is **3 times the industry average** and almost double the best performing El Teniente layouts through the redefinition of the work required to be completed by the loaders,
- The use of trucks to haul material from within the footprint to the primary crusher ensures **the same productivity rate from any drawpoint on the footprint**, increases the effective size of the largest fragment that can pass through the system, improves the overall production efficiency and lowers unit operating costs,
- Future expansion of the caving footprint results in **reduced capital costs** through the need to only mine the additional rows of drawbells and adding additional trucks to maintain the production rates over a longer haul distance to the existing crushers.

Incorporating post condition blasting levels into the mine plan aids in achieving an accelerated cave ramp up by repositioning the seismic events away from the Extraction Level whilst also reducing the fragmentation size in the lower caving columns.

ACKNOWLEDGEMENT

The author would like to acknowledge all of those in the caving community who have continued to push the boundaries of what we do. I also want to acknowledge and thank the late Professor Gideon Chitombo for his guidance and mentoring during my caving journey.

REFERENCES

Arancibia, E., Carrasco, F., Fuentes, S. & Guarda, J. (2008). Design of extraction layout for the Chuquicamata underground mine project. MassMin 2008 (pp. 3-14). Lulea: Lulea University of Technology, Sweden.

Brunton, I., Lett, J., Sharrock, G., Thornhill, T. & Mobilio, B. (2016). Full-scale Flow Marker Experiments at the Ridgeway Deeps and Cadia East Cave Operations. MassMin 2016 (pp. 141-150). Sydney: Australian Institute of Mining and Metallurgy, Melbourne.

Campbell, A. D. (2020). Recovery and flow in cave mining: current knowledge gaps and the role of technology in the future. in J Wesseloo (ed.), UMT 2020: Proceedings of the Second International Conference on Underground Mining Technology, Australian Centre for Geomechanics, Perth, pp. 77-104

Laubscher, D. H. (1994). Cave Mining - the state of the art. *J S Afr Inst Min Metall*, 279-293.