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Innovative Cave Mine Design for enhanced Safety, Productivity and Value

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Abstract

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 or increased footprint establishment costs.

Acknowledging the complex interactions of technical, design, implementation, and operational aspects of a Block Caving footprint, how can the safety, stability, caveability, productivity, ore recovery and financials be improved by redesigning the layout and associated materials handling and management systems?

1. What needs to change, in the design and establishment of caving footprints, to enable a reduction of 30% in the time taken to achieve nameplate production, without compromising the long-term productivity of the footprint?
2. What are the key economic parameters that influence the economic performance of a Block Caving mine and how can they be revised to improve the economic returns?
3. Which technical areas have the largest influence on the successful extraction of the target ore block and how can they be enabled in the mine design and execution strategies?
4. What design and operational strategies are available to minimize, and ideally eliminate, major hazards from a Block caving footprint?
5. What design, caveability, operational and management risks are reduced using the new footprint and what new risks are introduced?

This thesis is based on the hypothesis that a revolutionary new cave mining footprint utilising a 4-sided drawbell and an integrated on-level loading and hauling system is not only safer but technically, operationally, and financially superior to the existing industry layouts. The redesign will focus on the physical layout and the preferred materials handling system on the Extraction Level, with attention given to the key technical, construction and operational functions.

A new caving layout, Cube Caving^{TM}, has been created which fully integrates the drawbell and the undercut shapes to form an ultimate drawbell which is nominally 50m wide in both directions at the top and seamlessly aligns with adjacent drawbells ensuring all cave material will be directed to one of the drawpoints on the Extraction Level. Using an integrated loader and truck system ensures that each drawpoint on the Extraction Level has a similar production rate. The haulage logic on the Extraction Level uses the loaders only to extract material from the drawpoints and then tram for less than 50m to load a truck which then travels directly to the crusher installation to discharge its load. The associated productivity improvements of the layout result in it being 3 times more productive than the industry average and almost double the best performing El Teniente layouts.

Stability and Cave flow modelling conducted using data from Freeport-McMoRan's DMLZ mine indicated that there is no difference in the ore recovery of the Cube layout when compared to a moderate sized El Teniente layout (30 x 18m), when assuming no drawpoint losses due to damage beyond repair in the flow simulator. The stability assessment showed that the Cube layout had an order of magnitude less damage to the pillar cores compared to one of the largest contemporary El Teniente layouts (30 x 24m) with no drawpoints expected to be lost, whilst the El Teniente layout was forecast to lose several drawpoints. When combining the stability and the flow results together the Cube layout would recover all forecast material from the cave whilst the same could not be said for the El Teniente layout.

Economic and schedule assessments were completed providing information on the impacts of change and identifying additional focus areas of the research, including the cave ramp up rate. An option of blasting the lowest 200m of the cave column made it possible to increase the production ramp up rate through the extraction of blasted material without compromising safety as the influence area of the rock mass response is well away from personnel and key infrastructure.

A comparison of mine design and schedule was completed on the Carrapateena Block Cave project and the results indicated that the simplified Extraction Level geometry, schedule flexibility and relocation of the predominance of production drilling to the Undercut Level results in material reductions, ~40%, to the establishment schedule and costs, while the time to achieve nameplate production is halved with these all combining to deliver superior financial returns for the mine owner. Additionally, the ongoing Operating costs were identified to be 40 to 60% lower than the proposed El Teniente layout and the production rate resilience was identified to be higher with Cube Caving^{TM}.

Future work involves establishing a trial area within an established or new caving mine to confirm the modelling results for stability and ore recovery. The establishment and operational improvements can be assessed through footprint simulation work on the surface. Confidence in the logic of the FS4 code can be improved by more flow marker trial data from caving operations.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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Publications included in this thesis

No publications included.

Submitted manuscripts included in this thesis

No manuscripts submitted for publication.

Other publications during candidature

Conference abstracts

1. [1] **Dunstan G**, Cube Caving™, a new cave mine design for the future, *Proceedings of the 9th International Conference on Mass Mining*, Kiruna, Sweden, September 2024.

Contributions by others to the thesis

Anthony Allman of Antcia Consulting Pty Ltd contributed to the 4 dimensional design and scheduling of the Cube Caving™ concept as part of this thesis. He was also involved in assessing the real world comparison option.

Beck Engineering, led by Dr Alex Campbell, was contracted to undertake the cave flow and stability assessment scopes of work contained in this thesis.

Jacob Woods of Praeditos Designs and Drafting was engaged to draft the equipment sequence drawings for the new Extraction Level layout.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

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List of Abbreviations and Symbols

Abbreviations	
2D	Two dimensional
3D	Three dimensional
BC	Block Caving
BC1	Block Cave 1 (Carrapateena)
BC2	Block Cave 2 (Carrapateena)
COB	Crushed Ore Bin
Cube	Cube Caving™
CVO	Cadia Valley Operations
DB	Drawbell
DEZ	Disturbed Extraction Zone
DFN	Discrete Fracture Network
DMLZ	Deep Mining Level Zone (Freeport)
ESG	Environmental, Social and Government
ET	El Teniente
h	Hour
HIZ	Height of Interaction
HV	High Voltage
IMZ	Isolated Movement Zone
IT	Integrated Tool Carrier
LHD	Load Haul Dump machine
M	Million
m	metre
mm	millimetre
m^2	square metre
m^3	cubic metre
MHS	Materials Handling System
NSR	Net Smelter Return
NSW	New South Wales
OEM	Original Equipment Manufacturer

PC	Panel Caving
PC1S1	Panel Cave 1 Stage 1 (Cadia East)
PC2S1	Panel Cave 2 Stage 1 (Cadia East)
PC2S2	Panel Cave 2 Stage 2 (Cadia East)
REBOP	Rapid Emulation Based on PFC3D
ROM	Run of Mine
SLC	Sub Level Caving
t	metric tonne
TM	Trade Mark
tpd	tonnes per day
V	Volt

Symbols	
~	Approximately
>	Greater than
/t	per tonne
%	Percentage
$	Australian Dollars
”	inch
o	Degree Celsius

Chapter 1

1 Introduction

1.1 Background

Block caving is a mass underground mining method in which a block of ore is undercut and because of drawing the broken ore from the drawbells at the base of the block, the cave progresses upwards. Early caves were used to extract highly broken rock masses using a gravity-based system of grizzlies to transfer the ore to the haulage levels. Over the years there has been a transition to mechanisation with many of the current caves leading the underground adoption of machine automation. The competency and depth of deposits mined today is far removed from the original versions though the principles of the method and the layouts themselves, a connected series of drawbells, remains.

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. To add to this many of the new large-scale deposits being discovered are deeper than previous finds 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.

These are:

- rock cutting tools for development without explosives,
- automation and remote operation,
- electric or battery powered hauling and loading units,
- environmental monitoring of the work areas,

- computer supporting systems for autonomous operations,
- traffic control/collision avoidance,
- equipment health and performance monitoring,
- cave tracking and monitoring, and
- simulation of activities to improve scheduling and workforce capabilities.

Block and Panel Caving Extraction Levels (Extraction Levels) are designed as a series of compromises taking into account many factors including, but not limited to:

- Footprint size and orebody caveability.
- Production rate and drawpoint materials handling strategy.
- Pillar stability and drawpoint spacing.
- Fragmentation and ore recovery.
- Drawbell and undercut interaction.
- Stress and Geological structure orientation.
- Undercutting methodology and abutment stress management.
- Ventilation requirements.
- Level infrastructure and operating philosophy.
- Establishment costs.
- Deposit economics.

Due to the wide range of technical areas involved in the successful design and operation of an Extraction Level footprint there has been an isolated approach taken to the research conducted to date with limited research into pulling all the areas together and reviewing how they operate as a complete system, based on the conference proceedings and industry research papers reviewed. Much of the research focusses on a narrow technical field and assumes consistent rock mass properties and uniform operating conditions, though it is well documented and understood that rock has a number of imperfections which change its behaviour.

Rock mass properties have conflicting impacts on many of the key design criteria for Block Cave mining. The author compiled the diagram shown in Figure 1 to illustrate how the various design parameters are impacted. In weaker rock masses the fragmentation will be finer resulting in narrower draw zones, though to ensure stability the pillars between the drawbells need to be substantial which results in a high likelihood of isolated draw. In contrast more competent rock masses will generate a coarser fragmentation and wider draw zones but also a higher probability of oversize material resulting in flow and production interruptions while the stronger rock allows for smaller pillars and a greater possibility of

interactive draw depending on the extraction strategy.

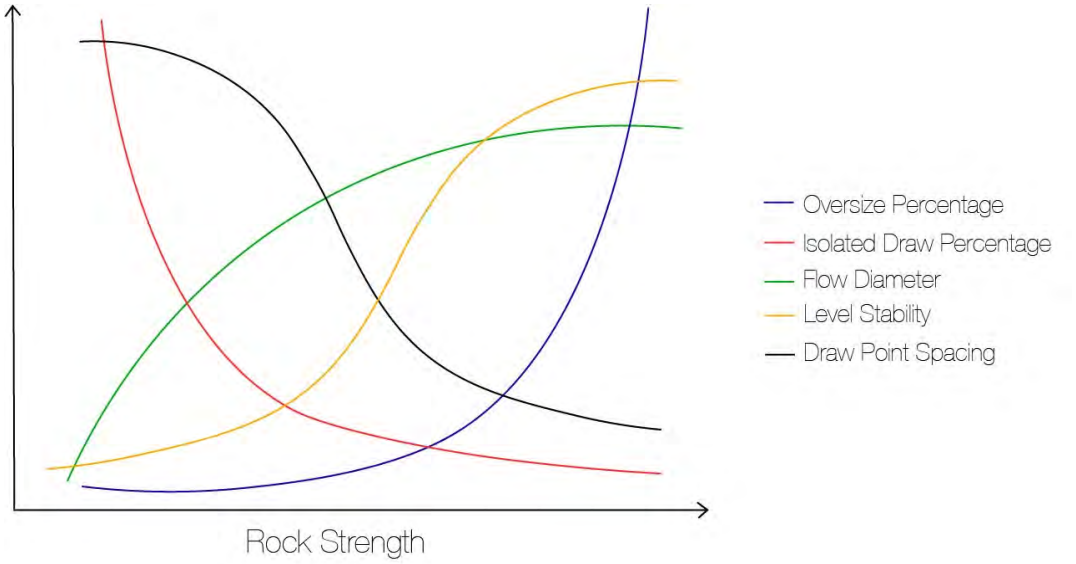


Figure 1: Rock Strength Variables (developed by Dunstan)

Many of the current and proposed Extraction Levels contain a range of rock mass properties with conflicting impacts on level stability, draw cone size, flow, and fragmentation. As an example, many companies look to modifying the draw control practices over the life of an Extraction Level to push the production limits for the footprints and improve the economics of the mine but this is only one variable in the successful long term execution of a caving footprint.

When designing an Extraction Level, there are several inputs which need to be considered that then lead to decision points as to the effectiveness of the layout and ultimately whether it is the correct mining approach for the orebody. A simplified flowchart outlining the key inputs and decision points was developed as part of this thesis by the author and is shown as Figure 2.

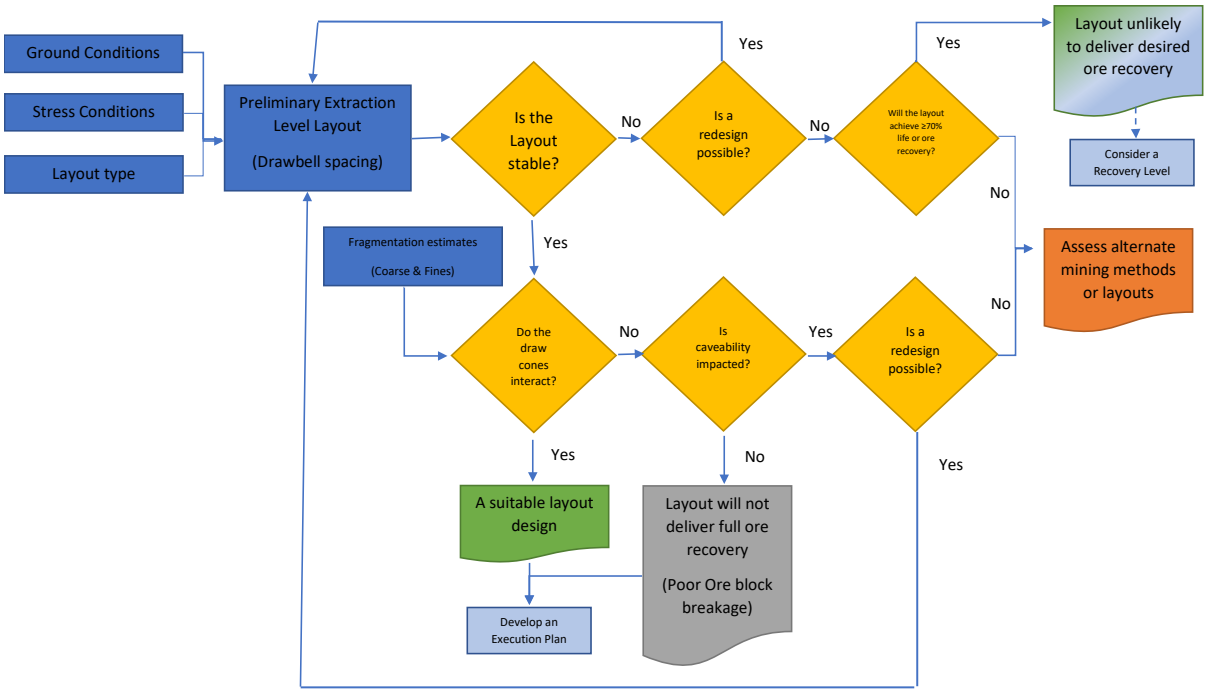


Figure 2: Extraction Level Layout decision flowchart (Dunstan)

New mine design strategies will be driven by how the rock responds (stress and fragmentation), by new and emerging technology, and to mitigate future operational issues. The first approach the basis of this research, is to acknowledge the inherent variability in the in situ, and ultimately the caved rock mass, and apply a design and mobile (rubber tyred) extraction system which both embraces and normalizes for this variability. The second approach will see the incorporation of technologies to engineer the rock masses to conform to a set of design criteria, i.e., fragmentation size, to enable the implementation of a predetermined layout and predominantly fixed extraction system.

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 footprint locations have deepened as the El Teniente layout provides a more stable rectangular pillar with a simpler development approach.

The current drawbell layouts create a series of stagnant zones between the mobilized extraction or flow zones in the lower portion of the cave column. These stagnant zones

result from the poorly integrated drawbell and undercut geometry that requires additional material to be blasted which compromises both the ore flow from the drawbell and the in situ pillar capacity. Ultimately leading to the recompacting of the blasted, but unrecovered, cave material which generates additional vertical load onto the remaining in situ rock pillars and compromising the stability of the Extraction Level.

Industry knowledge, accepted by some, 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 of the draw zones on the footprint are interacting this is called the Height of Interaction Zone (HIZ) (Laubscher 1994) as shown in Figure 3 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.

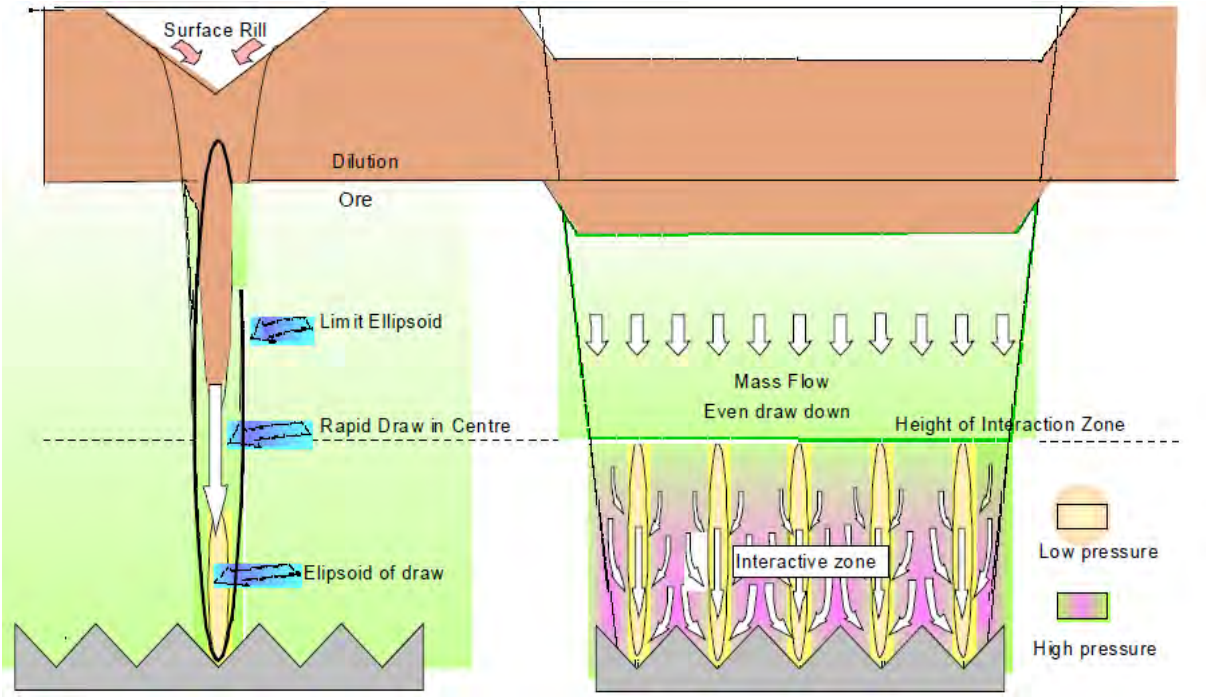


Figure 3: Cave Flow Definitions (Laubscher 1994)

1.1.1 Stages of Block Caving

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.

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 are as intact as possible.

Caving is initiated by mining an undercut until the hydraulic radius of the rockmass is reached or exceeded. As the broken material from the undercut area is extracted the rockmass above will fracture and fall into the void created. Horizontal propagation of the caving area will continue as more undercut area and drawbells below it are established, while vertical cave propagation is achieved by drawing more material from the drawbells. There are three undercutting sequences, i.e., Pre, Post and Advanced, with Post and Advanced now being the most widely used in industry.

Post undercutting involves establishing the drawbell first and then firing the undercut down into the void created by the drawbell. This sequence allows for confirmation of the drawbell firing and larger undercut blasts due to the void available in the drawbell. It also enables a faster production ramp up and has all the material report to the Extraction Level, which is set up for efficient material movement.

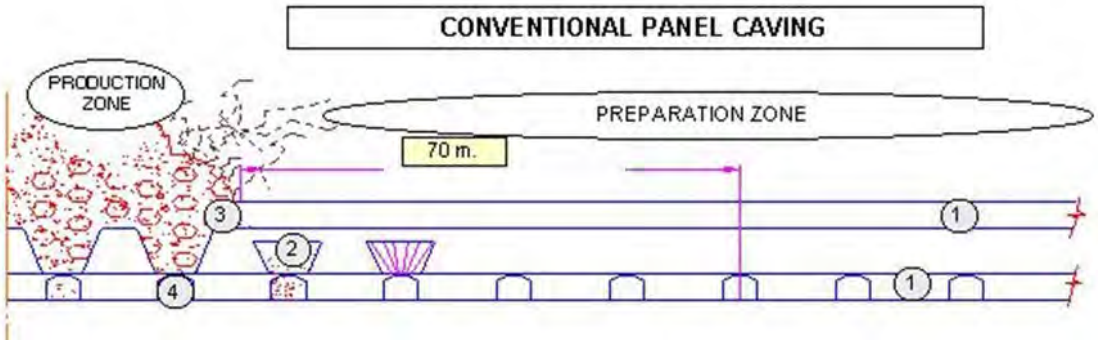


Figure 4: Post Undercutting sequence

The disadvantages of Post undercutting include the exposure of personnel on both the Undercut and Extraction Level to the increased abutment stresses during cave establishment. Also depending on the separation between the undercut and Extraction levels a small pillar is created between the top of the drawbell and the undercut development which can act as a stress corridor and become unstable.

This undercutting sequence is currently the preferred option for Codelco (Pardo 2016), Freeport McMoRan's Henderson Mine (Callahan 2016) and Newmont, formerly Newcrest, (Lett 2016).

Advance undercutting involves establishing the undercut first and then firing the drawbell behind the advancing undercut front once a suitable stress shadow has been established. This sequence provides stress coverage of the Extraction Level turnouts and the drawpoint development.

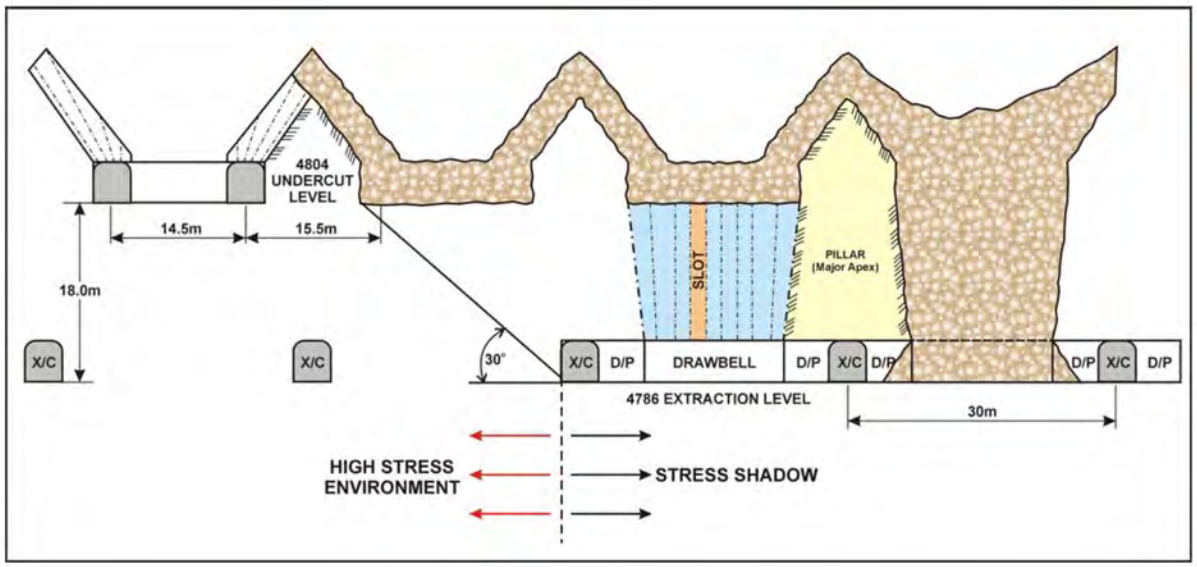


Figure 5: Advance Undercutting sequence

The disadvantages of the sequence are the limited undercut firings due to the limited void available, additional activities to remove the swell material from the Undercut level and the inability to positively confirm the successful firing of the drawbell. The sequence also links the Undercut and Extraction level activities together to manage stress abutments so a delay in any task on either level slows the undercut advance.

Freeport McMoRan (Grasberg, DMLZ) (Brannon 2016), Rio Tinto (Oyu Tolgoi) (Crook 2018) and New Afton are currently using this establishment sequence.

Depending on the undercutting sequence being employed to establish the cave will determine how much of the Extraction Level is developed prior to cave initiation. In the Advance undercutting sequence, the general approach is to only develop the Extraction Drives prior to the undercut front with the Drawbell development started once the undercut has passed over the proposed turnouts and provides a stress shield. In the Post (or conventional) undercutting sequence the drawbell development needs to be established prior to the undercutting front to allow the drawbell to be established early, this leads to most of the Extraction Level being developed ahead of Cave initiation.

With increasing depth and stress considerations the excavation sizes on the Extraction Level have been getting smaller with an increased amount of ground support to withstand the conditions. This has had a negative impact on the development rates and the size of equipment available to develop and then operate on the Extraction Levels.

As the Undercut Level, including the Apex Level if required, is expendable it doesn't require the same level of precision mining. Though with the increasing stresses as the cave is established and retreats across the undercut level the excavations and ground support need to be able to withstand dynamic events. The development profiles are mostly influenced by the equipment requirements to drill the undercut rings to ensure uninterrupted breakage of the base of the ore block.

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.

Based on the experience of the author 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 significantly changed 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
- the highest levels of interaction occur between various disciplines, equipment and personnel leading to high levels of safety risk.

After reviewing numerous caving projects and discussing their performance with industry colleagues the consensus is that to be successful during the cave establishment period history has highlighted that there are a limited number of important rules to follow, with three key ones being:

- ensure that the project has sufficient funding to complete the identified scope,
- once you commence undercutting DON'T STOP,
- do not make wholesale changes during the cave establishment period unless you have no other option.

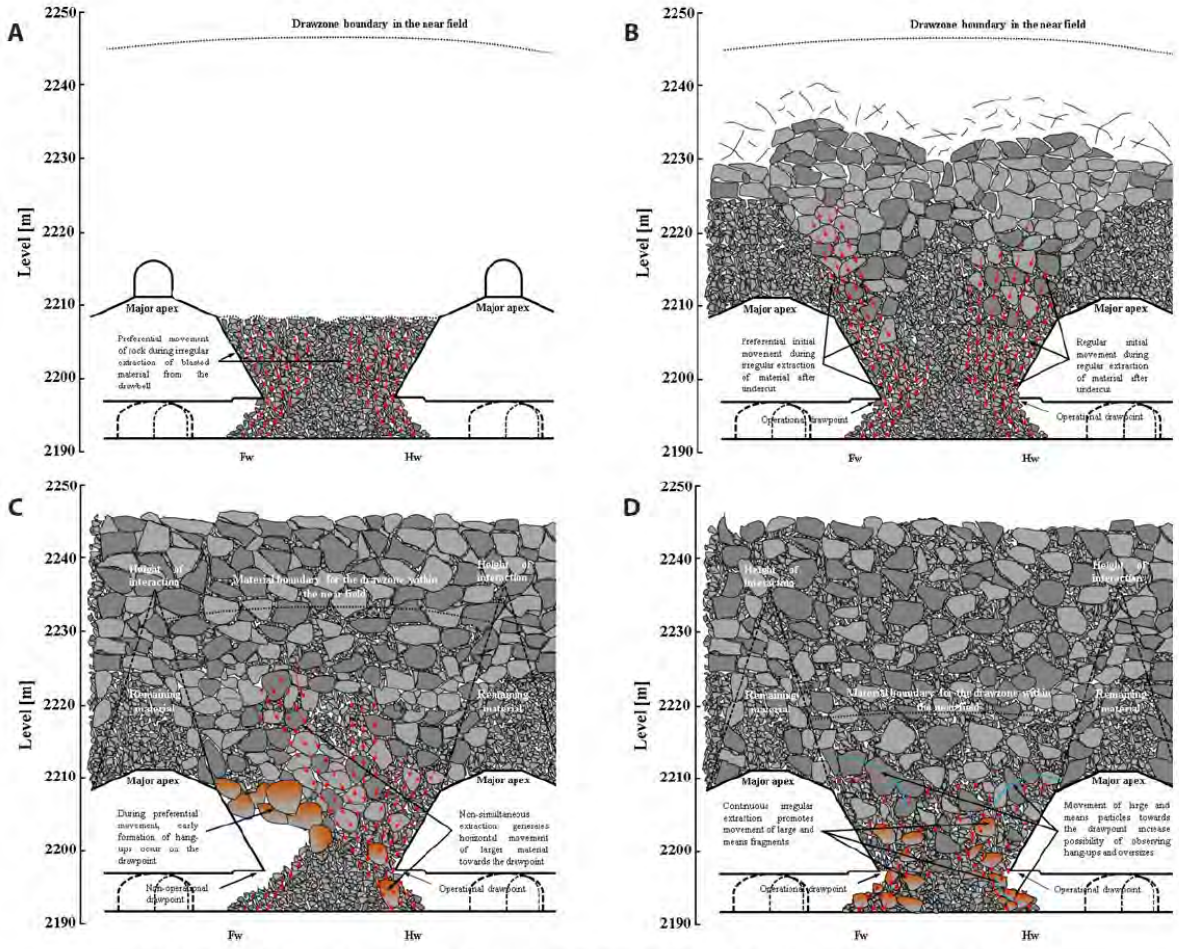
Over the last few decades, the caving industry has attempted to "engineer the Cave" by utilising Pre-Conditioning techniques including Hydraulic Fracturing, Confined Blasting, or a combination of the two. The issues associated with these techniques is that it is difficult to quantify the change in the rock mass and the associated caving performance compared to if they were not utilised. (Catalan 2014) undertook the largest full-scale trial of this theory during the establishment of Cadia East Panel Cave 1 Stage 1 (PC1S1) at Newmont's Cadia Valley Operations in NSW, Australia (with this author responsible for the implementation and execution of the associated physical works and data collection). His theory was to utilise

intensive pre-conditioning by combining hydraulic fracturing of the 400m high ore block and confined blasting using 150m long upholes from the Undercut Level to adjust downward the rock mass rating in the lower 150m of the cave column by one classification grade to improve the cave propagation, initial production rates and reduce the magnitude of seismicity in the areas near where personnel would be undertaking caving related tasks. Despite the use of many detailed measurement techniques and small-scale analyses, the hypothesis of Catalan's research was not proven yet anecdotal evidence gathered by comparing the cave establishment performance of PC1S1 and Panel Cave 2 Stage 1 (PC2S1) some 200m lower and in technically poorer rock suggests that the intensive preconditioning program may have had some positive influence on the PC1S1 cave.

Learnings from Catalan's intensive approach are that implementing hydraulic fracturing and/or blast conditioning in the confined pre-caving environment is less effective than applying them in a post-caving situation where the cave itself acts as a free face. Numerous caving operations around the world have used these same techniques to post condition a stalled or distorted cave to attempt to rectify a poor or underperforming cave establishment period (Talu, van As et al. 2010).

Fragmentation reporting to the drawpoint during the Cave Establishment period is particularly important as it directly influences the cave production 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). The initial fragmentation reporting to the drawpoints is fine as it is produced by the blasting of the drawbell and undercut material, 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 6 shows the style of undercut can also influence this early-stage fragmentation as some designs create a stress shadow above the drawbell (between the undercut apices) which impacts the initial flow of ore to the drawpoint (Brunton, Lett et al. 2016) and increases the fragment size. Large fragment sizes at any stage, though particularly early, in the draw column create problems due to the drawpoint being taken offline while the oversize fragment on the rill, or worse, within the drawbell is dealt with (Figure 7). During the early initiation of the cave when there are limited drawpoints available, having some offline due to oversize material impacts the draw schedule and the potential production available from the footprint. Palabora and Ridgeway Deeps are just two examples where early oversize material had a materially detrimental impact on the cave establishment period of the mine, in fact at Palabora it led to long term stability issues on the footprint due to the limited draw opportunities available and the time it took to turn over

drawpoints led to significant cave weight being placed on the Extraction Level pillars.



Conceptual model of gravity flow in the near field. (A) Draw of blasted rock from drawbell; (B) initial draw of material from undercutting (up to 15 m above undercut level (UCL)); (C) draw up to 25 m above UCL; (D) draw up to 35 m above UCL.

Figure 6: Conceptual model of gravity flow in the near field (Brunton, Lett et al. 2016)

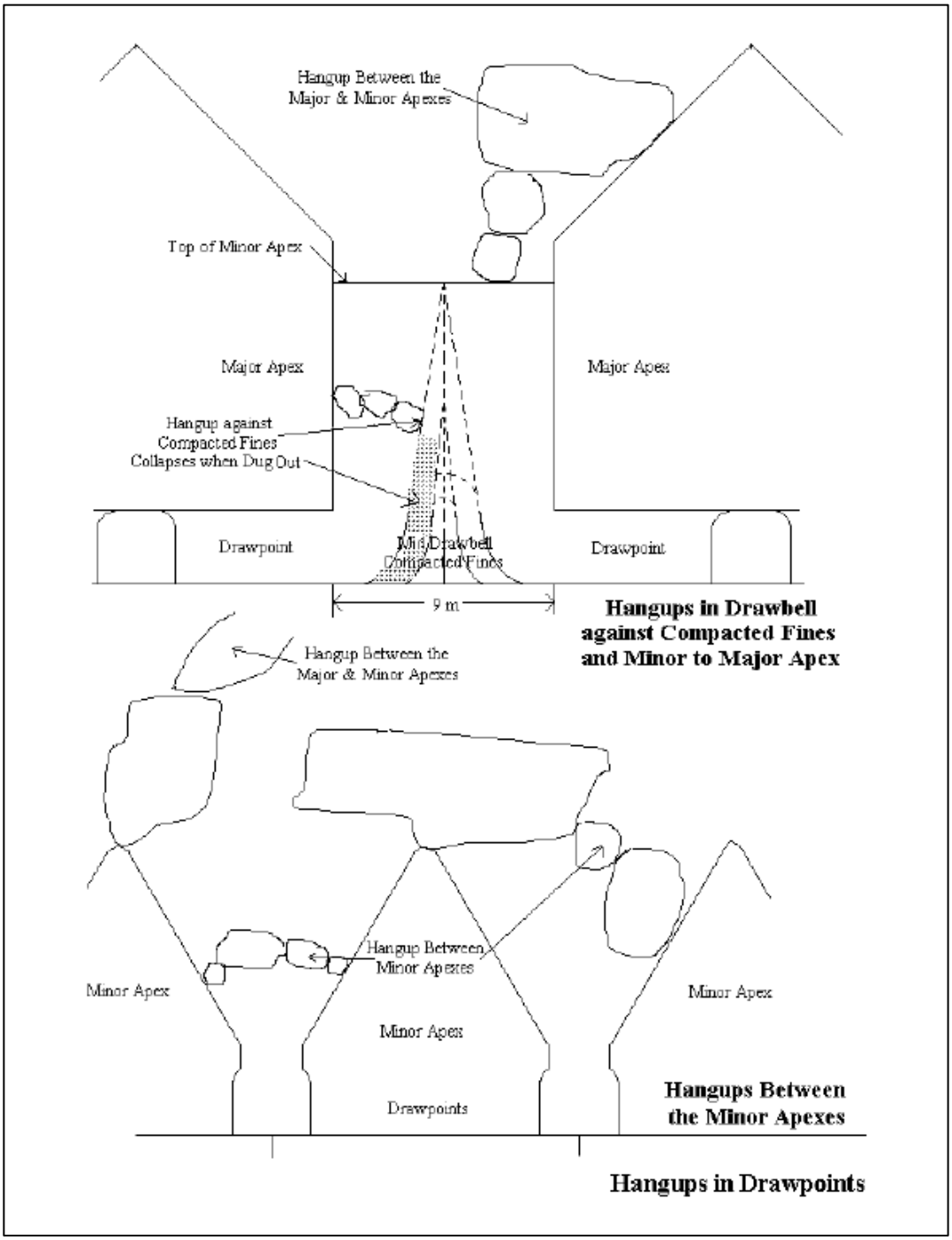


Figure 7: Potential Hang up locations in a drawpoint (Laubscher 2000)

Several recent caving mines have investigated the use of high or double lift undercuts to increase the amount of blasted material generated during the undercutting process (Vink 1995), and also to increase the travel distance of the initial Cave back fragments in an attempt for some attrition within the newly established ore columns to reduce the size of the fragment by the time it reaches the drawpoint. The downside to these increased undercut heights is the additional loading which needs to be conducted to keep the undercut front moving thus potentially increasing the risks associated with slow undercutting rates (Brown 2007).

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.

Examples include:

- limiting the tramming of production ore through the construction and development zones,
- minimizing the amount of ventilation breakthroughs which diffuses the airflow across the level and increases the fume clearance times post development and production firings,
- understanding the impacts of exclusion zones for certain sections of the mine following major changes in the size of the undercut and allowing the host rock time to redistribute the stresses associated with the caving footprint increase,
- clearly identifying the timing requirement of each task and the pre and post tasks linked to it,
- limiting the amount of permanent infrastructure installed during the establishment of the cave to limit the amount of rework required once the ground around the Extraction Level has resettled post the undercut and caving being established, items include concrete aprons, concrete or paving style roadways and fixed piping,
- relocate as many tasks as possible to the Undercut Level to reduce the congestion on the Extraction Level.

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.

Cave Establishment is arguably the most critical stage in the life of a Block Cave. During this stage the undercutting process is initiated, the drawbelling commences and the critical span of the rock mass is exceeded leading to the natural breakage and propagation of the rock mass. During this stage it is important to ensure that no bridges, or caving span

interrupts, are created while undercutting the target ore block and that the establishment of drawbells is in a geometry which promotes caving of this target ore. Speed is critical during this time period as is successful execution therefore it needs to be well planned as changes and recovery are difficult. The main reasons for ore loss are active during this stage, namely underbreak of the target ore block and drawpoint loss due to cave stress redistribution.

During this stage the materials handling system is installed to ensure that the mine can keep up with the potential material generated by the cave. The propagation of the cave and the amount of material extracted is closely monitored to ensure that there is not a significant airgap forming due to the cave back stalling or conversely that enough material is being extracted to ensure that the cave back does not become buttressed and stop propagating.

Due to the significance of this stage, it is a highly monitored and controlled phase with the focus on safety and caving rather than production from the drawbells. With the nature of block caving, you only get one go at establishing the cave and there are few levers available to recover a poorly established cave.

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.

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, increased wear of the brows and tunnel convergence all leading 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 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 neighbouring drawpoints.

The technical monitoring and effort during the Closure stage is like that during the Cave Establishment phase.

1.1.2 Footprint Options

As the existing El Teniente layout is used in deeper and more challenging conditions, the operational impacts of utilising 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 available in the current layout to 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 only 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 only options 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 8) 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 9) or inside (Figure 10) the footprint or potentially a combination of both.

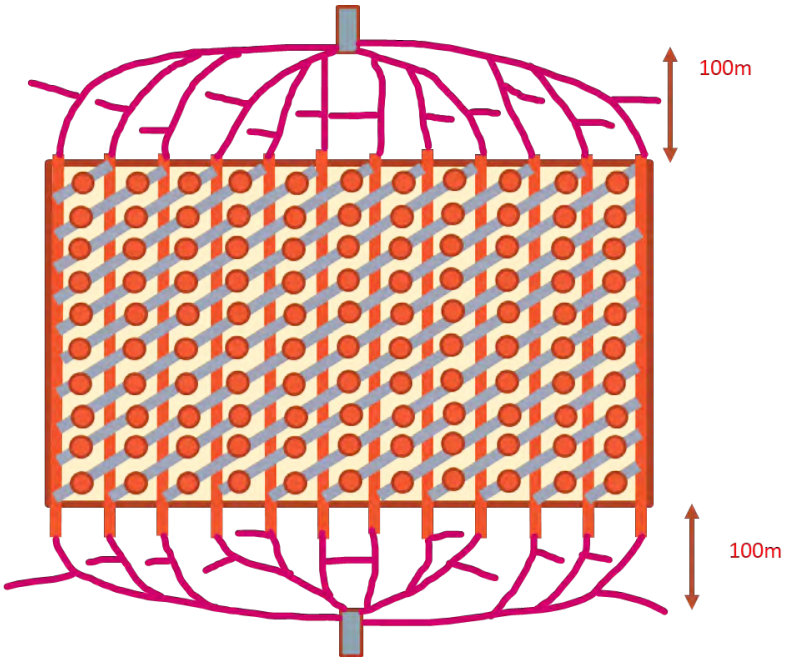


Figure 8: On footprint Crusher configuration (Dunstan)

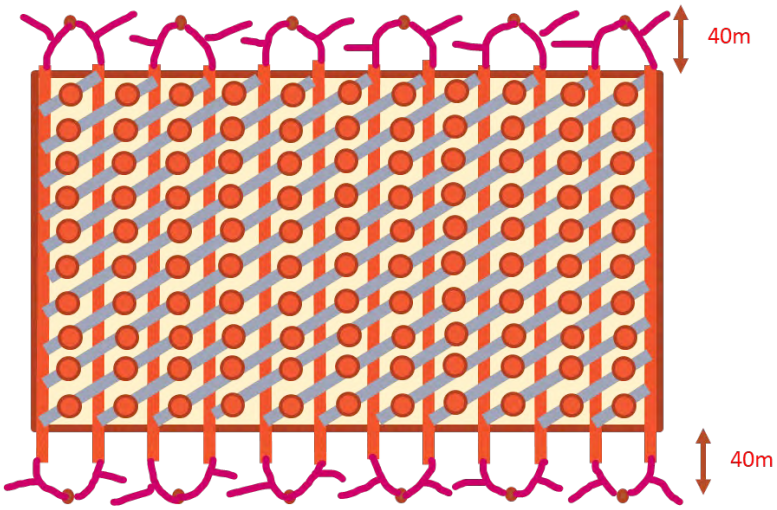


Figure 9: External Ore pass *configuration (Dunstan)*

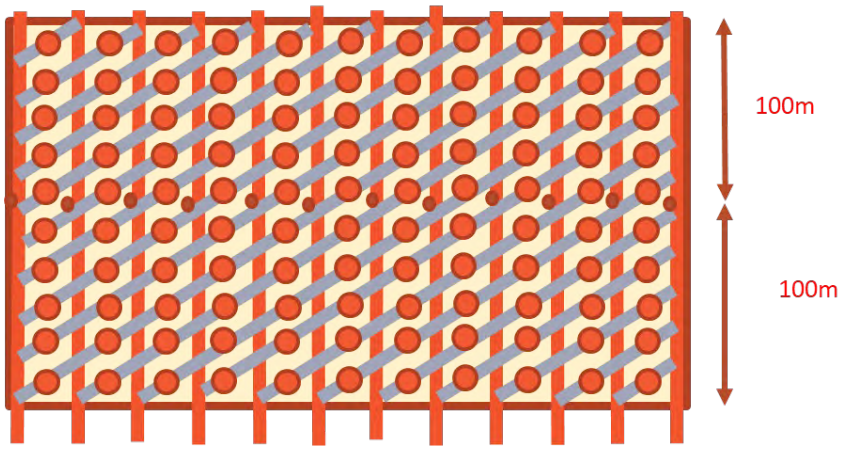


Figure 10: Inside footprint Ore pass *configuration (Dunstan)*

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 hang ups occurring in the ore pass. Depending on the diameter of the ore pass the grizzly constraint could be as small as 700mm, though they are generally between 800mm and 1,000mm. The key operating issue with grizzlies is that they are generally static and similar to tipping flour into a sifter, even if the rock fragments are smaller than the grizzly aperture the way they are tipped onto the grizzly by the LHD generally results in a mounding of material on the grizzly through the interlocking of fragments which needs to be cleared either by the LHD sweeping its bucket over the grizzly, which adds non-productive time to the LHD's cycle, or a rock breaking unit to knock the interlocking particles apart. The impact of the grizzly units is that they significantly reduce the size of the fragments which need to be treated on the Extraction Level, they are now much smaller than the LHD bucket and not obvious in the drawpoint muckpile. Once the fragments have passed through the grizzly into the ore pass they then need to be collected and transferred to the primary crushing unit, regardless of the haulage level system, truck

or train, this results in large excavations at the base of the ore passes to load the transport units. The loading configuration at the base of the ore pass also adds an additional choke point in the system as the chute, or similar, needs to laterally load rocks into a truck or train with the weight of the ore in the ore pass acting vertically leading to friction and conflicting forces on the brow of the ore pass and chute system. With the grizzly constraint having reduced the maximum fragment size being delivered to the crusher, the size and style of crusher required is different to that for a direct tip from the drawpoint system. The smaller fragments from the ore pass system may result in the crusher which is required, being overly large to ensure that it can deliver the target production from the mine though it acts like a mechanical sieve rather than a crusher as there are little to no decent fragments for it to crush.

The accepted industry standard for an "oversize" fragment is $2m^3$, though the logic and reasoning behind this number has been lost over the years. Through discussion with industry peers who worked in the early mechanical Block Cave mines this sizing came from the maximum lump size that the original mechanical loaders could fit in their buckets. This sizing whilst useful as a benchmarking measure to compare the estimated fragmentation at one mine to another isn't appropriate to determine the number of secondary treatments required to keep production flowing on the footprint if it does not match the constraint measures of the materials handling system on the Extraction Level. Most mines utilising an ore pass system use between a 2.4m and 3m diameter ore pass which results in a grizzly aperture on top of the pass of between 0.8m and 1.0m. The resulting fragment size to pass freely, noting that this doesn't preclude the material mounding on top of the grizzly from smaller particles interlocking due to the tipping nature of the LHD, through these grizzly dimensions is between 0.3m to 0.9m or $0.01m^3$ and $0.6m^3$ respectively. For a footprint targeting ~100,000t per day this equates to between 75,000 and over 600,000 fragments per day which need to be attended to for a second time. This compares to an estimate of 1,500 to 6,000 fragments needing treatment if a rock size of $2m^3$ is used. The impact of this underestimation in production disruptions has resulted in a significant financial and reputational impact on a number of mines in the last couple of decades, including Palabora, Ridgeway Deeps and sections of the El Teniente mine. To overcome the issue the mine operations team prioritises the secondary breaking fleet over the production loaders until such time as the fragmentation within the cave columns fines up sufficiently to remove the constraint.

To overcome the limitation of one loader operating between the drawpoints and a designated tipping location, an alternative loader operating configuration that has been

utilised in select areas of a cave for a limited period is a loop configuration to enable additional LHDs to be operated in a restricted area, as shown in Figure 11. The drawback to this configuration is that the tramming distances of the LHDs are significantly increased compared to the more traditional 1 LHD per tramming section of an Extraction Drive. This loop configuration may enable some footprints to tip direct to a crusher and not introduce ore passes though it is untested at high tonnage rates across an entire Block Caving footprint.

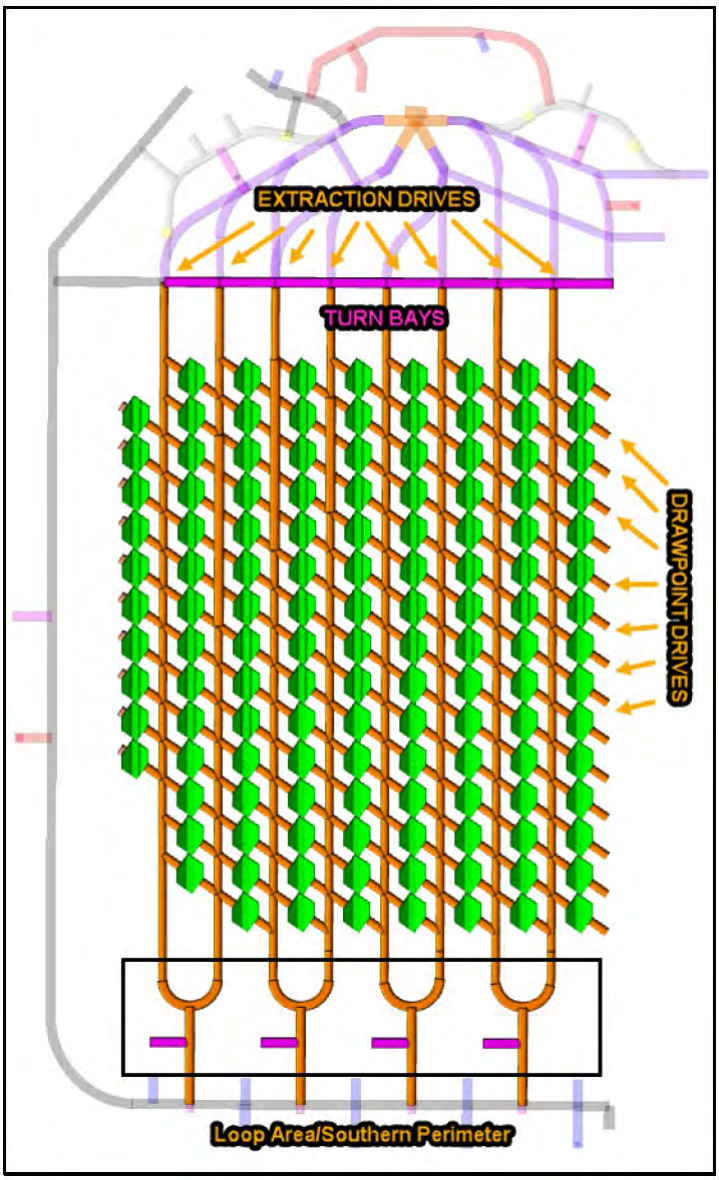


Figure 11: Extraction Level Loop System (Mariager 2024)

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 a given time period to ensure the cave column is drawn evenly to maximise ore recovery, defer dilution entry and to ensure 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. Whilst the draw strategy will look to average out the tramming distances the longest tramming route drawpoints will always push up this average. In some cases where the loaders are direct tipping to the crusher the tramming lengths may vary between 100m and almost 500m, whilst for ore pass systems the distances may vary from 10m to 250m. The use of the El Teniente layout also means that for half of the drawpoints the loader must turn around somewhere in the cycle or utilise another dumping point. This is not the case for the Offset Herringbone layout as all the drawpoints are arranged so that the loader has a consistent operating direction in the Extraction Drive between the drawpoint and the dumping location (ore pass or crusher), though as mentioned previously this layout has lost favour in recent years due to the shape of the pillars and the complicated development sequencing of the drawbells.

The productivity rate of existing Block Cave footprints is limited by the following factors (Encina 2008, Orellana 2016, Gomez 2020, Le-Feaux 2021):

- 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.

With the increasing depth and more challenging environments for large scale mining the existing dominant layout for block cave mining, the El Teniente layout, is being pushed to its limits. With the increasing requirement to improve stability of the footprint to maximise the ore recovered on the Extraction Level the spacing of the drawbells has been increasing over the last few decades with many caves now utilising spacings of >30m x >20m compared to the caves of the 1990's at 26m x 16m. The increase in Major and Minor apex pillars whilst improving the stability of the Extraction Level comes at a cost to the ore recovery should the draw columns no longer overlap and become isolated or independent of each other. This isolated draw scenario directly impacts the cave propagation and the ore reserve recovery and potentially the stability of the level as the vertical cave loads are no longer shed across the footprint but can find isolated zones of static material which leads to point loading of pillars and potential drive collapses. To support the wider drawbell

spacings, the fragmentation of the cave column material needs to be coarser to develop wider draw columns which then have the chance to overlap. The downside to the coarser fragmentation is the risk of increasing the number of production interruptions in the materials handling system between the drawpoint and the primary crusher. The impact is somewhat mitigated if the production system involves an LHD tipping directly to the Primary crusher, though if there are ore passes between the drawpoint and the crusher the coarser material will need to be broken on the level to ensure it makes it through the system. This additional breakage results in non-productive time for the loader and likely the involvement of another type of equipment to assist getting the ore to the crusher.

If the spacing between the drawbells cannot reasonably be increased to maximise the pillar dimensions for the expected rock fragmentation, then the only other option available is to reduce the width of the Extraction Level development. This decision impacts the size of the production fleet units which can safely be operated in the level thus reducing their production capability. To offset the production decrease in the smaller fleet whilst maintaining the target production rate the length of tram for the LHD must be reduced. Generally, this reduction will result in the need to introduce ore passes into the materials handling system as the tramming length to an on-level primary crusher will be prohibitive. (Encina 2008) proposed removing the LHD from the system and replacing it with a continuous mechanical alternative utilising a hydraulic dozer blade in the drawpoint on to a panzer conveyor and then into a crushing unit. This system was tasked with increasing the productivity of the level by >40%.

Figure 12 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.

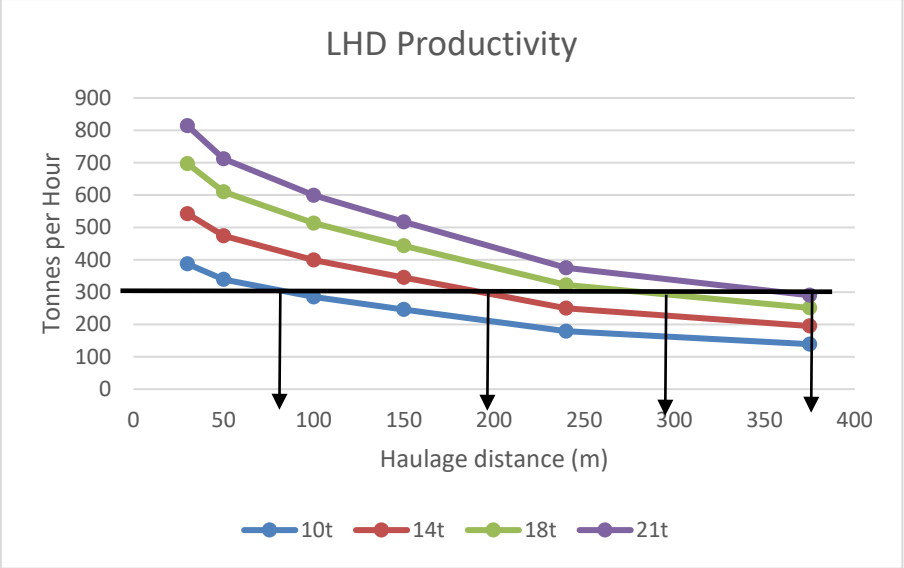


Figure 12: Loader Productivity by size and distance (Dunstan)

1.1.3 Conclusions

The existing footprints are based on observations from the 1960's and 70's in caving situations, depth below surface and rocktype, no longer relevant to the modern caving mines. As the modern mines continue to be deeper with higher stresses the existing footprint geometries are being stretched beyond their stability and flow capabilities resulting in poor recovery results from large upfront investments.

The challenging operating conditions being experienced in the current caves, and predicted in the future caving projects, result in a trade-off being made between stability of the footprint, recovery of the ore block and production rate. This trade-off is leading to suboptimal outcomes and reputational damage to the deep caving community.

The production rate increases being targeted from the current and future caving footprints require a highly efficient footprint. This efficiency is achieved through the largest loader size operating in stable Extraction Drives, short to medium travel routes for the loaders and high availability of the loading (drawpoints) and dump (orepasses or crushers) points. With the requirement to improve the stability of the footprints the size of the operating drives is reducing to maximise the rock pillars available to withstand the ground and cave loading stresses being applied to the footprint. These smaller drives result in reduced openings in the drawpoint for the cave material to pass through which impacts the availability of the drawpoints as the smaller openings result in increased hangups with the cave material particles locking up more frequently. The smaller the operating drives, the smaller the loaders that can operate in them. With the reduced loader size then the tramming routes

need to be reduced to maintain the productivity rates, leading to the requirement to incorporate orepasses within the footprint or close to the edge of the cave. The incorporation of orepasses significantly reduces the size of material that smoothly transitions through the system as the orepasses will have a grizzly on them to manage the particle size inside the pass to reduce the chance of hangups. The ore passes also require a haulage level below the Extraction Level to move the material from the orepasses to the crushers, either via loader, truck or train. This Haulage Level is an additional expense, and its location is dictated by the abutment stresses wrapping around below (keel stresses) the Extraction Level. These keel stresses also impact the scheduling of the establishment of the Haulage Level and the associated orepasses, usually delaying the installation of the orepasses until the keel stresses have been maximized to provide a stable environment to establish the orepasses in. The inclusion of a Haulage Level allows for the primary materials handling system to be located in a stable location off the footprint which can be accessed by multiple caving footprints if required.

Where the loaders are set up to tip directly to the primary crusher on the footprint to remove the need for a Haulage Level then the productivity of the footprint is determined by the longest tramming route of the loader, as all operating drawpoints are required to be drawn from as evenly as possible to ensure the optimal flow of material within the caving column. Prioritizing the draw of material from the drawpoints nearest the crusher will assist in improving the production rate but will likely lead to a reduced overall recovery of the ore block.

Due to the volume of material targeted to be mined by the Block Caving method there is variability in the rock mass properties both across the designed footprint and within the vertical caving columns. This variability must be accommodated in the design of the Extraction Level, the cave establishment activities and the production approach. In addition to the rock mass variation the fragmentation of the cave particles changes over the lifecycle of a cave column and each stage has an influence on the performance of the footprint.

The future caving footprints need to account for the variations in rock mass properties, the increasing depth effects including stress, heat and water, ore recovery from higher draw columns including cave propagation impacts and the variability of fragmentation and the desire for higher production rates to match or exceed the metal production of the Open Pit operations they are replacing in the world markets.

Chapter 2

2 Literature Review

2.1 Extraction Level Design Criteria

2.1.1 Key Findings

The design of an Extraction Level in a Block or Panel cave involves the evaluation of a number of interlinked criteria (Arancibia, Carrasco et al. 2008), these are nominally:

- Stability
- Ore recovery
- Dilution management
- Productivity
- Materials handling system restrictions

Stability

The mine design must ensure, locally and globally, a stable layout to reduce the exposure of risk to personnel working on the level and to the production infrastructure. It is also critical to ensure access to the ore in the cave columns for economic returns to be realized. The stability of the proposed design needs to be validated through geotechnical analysis and modifications made as necessary.

Ore Recovery

The objective of maximizing ore recovery is a simple and obvious one, though how it is implemented is more complicated. There are many methods used to estimate the draw cones used as the basis of determining the drawpoint spacing. The operating criteria required for the LHD units that could be used to extract the material from the drawpoints plays a big part, as does the fragmentation expected in the cave column.

Dilution Management

The idealized approach to deferring the ingress of lower grade material (dilution) into the ore columns is that of quasi-simultaneous extraction which results in the uniform drawdown of the ore column, therefore holding back the ingress of dilution to the drawpoints at the

base of the column. This theoretical approach does not account for the inherent variability in the rockmass properties and the resulting variations in fragmentation and therefore propagation rates.

Productivity

The productivity of the level will be a combination of the materials extraction approach on the Extraction Level and how it integrates into the mines overall system. The ability of the on-level system to accommodate the variable fragment sizes will also impact the performance levels of the mine.

Materials Handling System restrictions

The impacts of the integration of the materials handling systems, on the level and the full mine, need to be considered as there are benefits and restrictions which influence the layout, functionality and costs of the Extraction Level. Areas which need consideration are the deformation impacts of the selected system, equipment impacts and the overall capacity of the system.

2.2 Extraction Level Stability

2.2.1 Key Findings

Stability of the Extraction Level footprint is paramount to the success of a block cave. Without a stable footprint the ability to extract the target ore from the cave is diminished (Campbell 2020). As footprint depths have increased the style of Extraction Level design has changed with the Herringbone layout dropping from industry where footprints are deeper than 1,100 metres. For Extraction Levels below this depth, the El Teniente layout is currently seen as the only viable solution due to its more regular pillar geometry. The downside to the El Teniente layout is the four-way intersections and the drawpoint orientations which require the loaders to operate in two directions in the drive to access all drawpoints which results in the need for a loader turning bay where there are only single sided tip points for the Extraction Level materials handling system. With the increasing depths and challenging rock mass conditions the pillar dimensions on the Extraction Level are being increased and this has impacts on the drawbell and drawpoint spacings across the minor and major apex pillars and also influences the size of the Extraction Drive and drawpoint development to maximise the in situ rock within the pillars. As the life of the Extraction Levels is being increased, the load on the pillars increases over time resulting in continuous deformation which may present as dilation of the walls resulting in smaller Extraction Drive and Drawpoint openings in which to operate.

With the increasing depth of the block cave footprints where previously both stability and optimal layout for ore recovery could be accommodated it is now becoming a decision of Extraction Level stability OR optimised ore recovery. Where ore recovery is selected for what will become unstable Extraction Levels, allowance for a Recovery Level below the planned Extraction Level is required, this level is usually designed at or below the Haulage Level, if one exists. Where stability is selected over cave flow there is an increased risk that cave propagation may not be achieved as the draw points are too far apart to enable consistent removal of material from below the cave back resulting in span interrupts and stagnant pillars which increase the likelihood of stress loading on the Extraction Level pillars.

A key consideration in the stability of the Extraction Level is the location of the tipping point to the materials handling system, either the crusher or ore passes. For the Extraction Level layouts where an on-footprint tip to the crusher ROM bin is selected a suitable standoff distance is necessary to ensure the stability of the large excavation associated with the crusher. This distance is influenced by the abutment zone dimension which increases

with depth and poor ground conditions. The larger the distance between the production area of the block cave and the crusher tip points, the lower the overall production from the footprint. This separation distance between the footprint and the crusher is a high stress area and requires the maximum pillar dimensions possible and sufficient ground support to keep the travel-ways open.

When the separation between the crusher and the active Extraction Level area is too large to sustain the desired production rate, then a transition to the use of an ore pass and lower-level haulage system is required. The ore passes might be located inside the footprint or outside the footprint on the edge, even inside the abutment zone, as the excavations are smaller than those required for a crusher. For ore pass systems designed within the footprint, consideration needs to be given to the impacts of pillar stability where the ore pass tipple is located and also to the timing of installation of the ore pass and its associated infrastructure relative to the abutment stress locations and cave loads to ensure stability of the ore pass system. The ore passes located outside the footprint have reduced exposure to the cave loads but are still influenced by the abutment stresses and its timing.

For layouts utilising ore pass systems, a Haulage Level is required to transport the material from the ore passes to the primary crushing system. These Haulage Levels are required to be located either directly below the active block cave footprint for the internal ore pass systems, or they might be a ring around the edge of the active footprint when servicing the external ore pass systems. Either way, their distance below the footprint is determined by the depth of the abutment zone and the size of the ore passes and the capacity requirement for the ore pass. The bases of the ore passes will generally contain a reasonably sized chamber to accommodate the loading infrastructure for the haulage system (trucks or trains), the size of this infrastructure chamber also influences the stability of the pillar between the Extraction Level and the Haulage Level. Whilst the lateral development for the Haulage Level can be completed prior to cave establishment, the vertical development associated with the ore passes may not be possible until after the abutment loads associated with caving have been removed from the ore pass locations to ensure the long-term stability of the ore pass system. Where the infrastructure is located outside the abutment zones, there is no restriction to the timing of the excavation of the materials handling system.

The infrastructure associated with the ventilation and water management on the Extraction Level is also influenced by the timing of cave establishment depending on its location on or outside the active caving footprint.

There are many computer modelling packages available to determine the stability and ground movement expected on the Extraction Level based on the pillar dimensions and associated infrastructure for the Extraction Level (Beck Engineering 2021), (Cuello and Newcombe 2018). These packages can also estimate the expected amount of deformation within the Extraction Level development including the impacts of ground support elements, the percentage of intact rock within the pillars and estimates can be provided relating to the impacts of wear on a draw point. Calibration of the models through the various phases of the Extraction Level life cycle is important to not only refine the model predictions but to improve the understanding of what inputs are important to validate and monitor.

It is important to identify as many mine-scale and local structures as possible on the Extraction Level as these have an influence on the integrity of the pillars, the redistribution of stresses across the footprint and potentially the cave shape (Beck, Hudson et al. 2016).

The orientation of the extraction drives and therefore the Major apex is generally parallel to the principal stress direction. Often the major mine scale structures are also parallel to the principal stress which can lead to instability issues. It is ideal to be able to intersect the major structures at almost 90 degrees to improve clamping of the structures and therefore level stability. The minor apex pillar acts as a brace and influences the stability of the major apex.

The Major apex pillar dimensions are defined by the shape of the undercut and the drawbell. As the Major apex pillar is “wrapped” around the Extraction Drive it is bounded by the drawpoint brow and the undercut. The Minor apex is the pillar between adjacent drawbells along one side of the Extraction Drive (Figure 13). The dimensions and integrity of these pillars is crucial to the viability of the Extraction Level as they are required to initially withstand the dynamic abutment stresses during the establishment of the cave and then when the cave has passed over them the load requirement changes to the static vertical load associated with the cave material. The integrity of the pillar cores has been identified as a critical component in the ability to successfully rehabilitate an area post convergence (Beck, Hudson et al. 2016) or if it will continue to yield. The Minor apex pillar acts as a brace to the Major apex pillar thus improving its load bearing capacity.

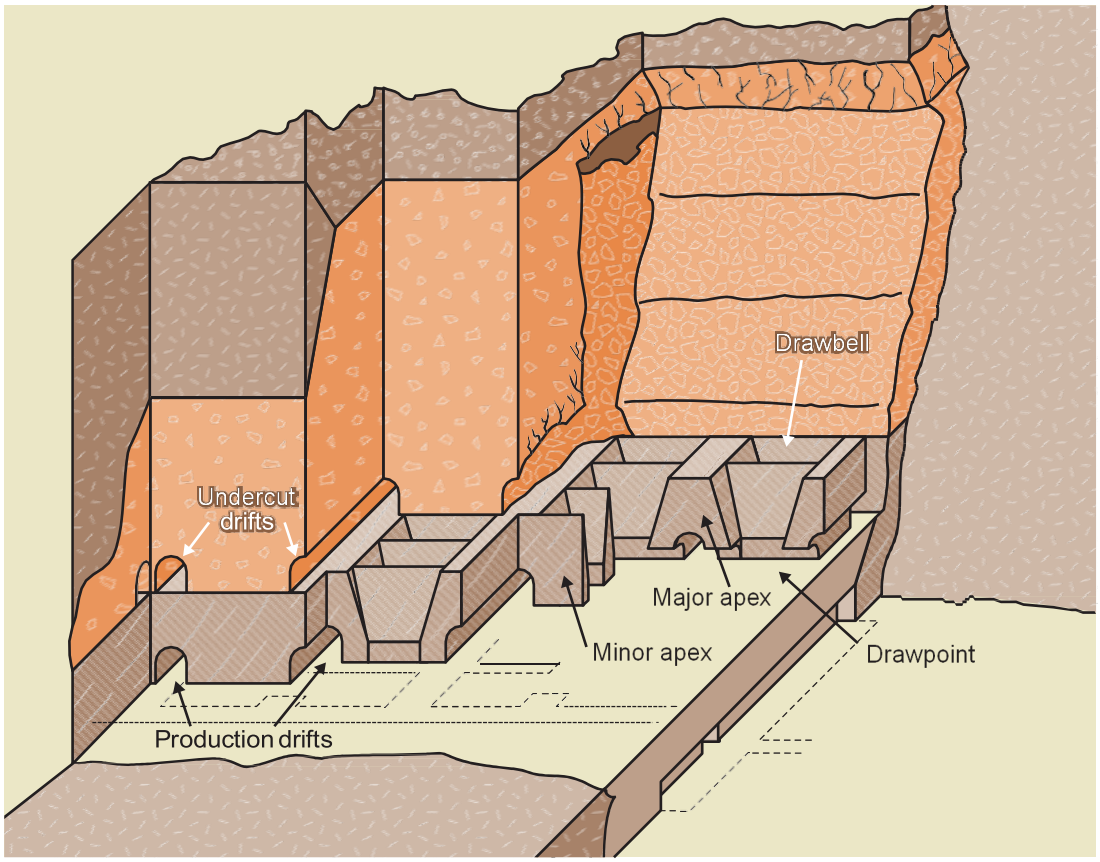


Figure 13: Diagram illustrating the positions of the major and minor pillars (Laubscher, Guest et al. 2018)

The excavation ratio on the Extraction Level is a measure of the rock pillar remaining against that removed for the installation of Extraction Drives and Drawbells. It is generally accepted that the higher this percentage the more stable the Extraction Level, though this measure does not account for the orientation of the pillars or the integrity of the pillar cores.

There is debate relating to which of the two most dominant layouts, El Teniente and Offset Herringbone, has the better pillar stability. The El Teniente layout (Figure 14 right) results in more rectangular bases to the Minor apex pillar though this is offset by the four-way intersections generated by having the drawpoint drives aligned opposite each other. The Offset Herringbone layout (Figure 14 Left) has a more angular base to the Minor apex and the Major apex has alternating buttressing with the offset drawpoint turnouts.

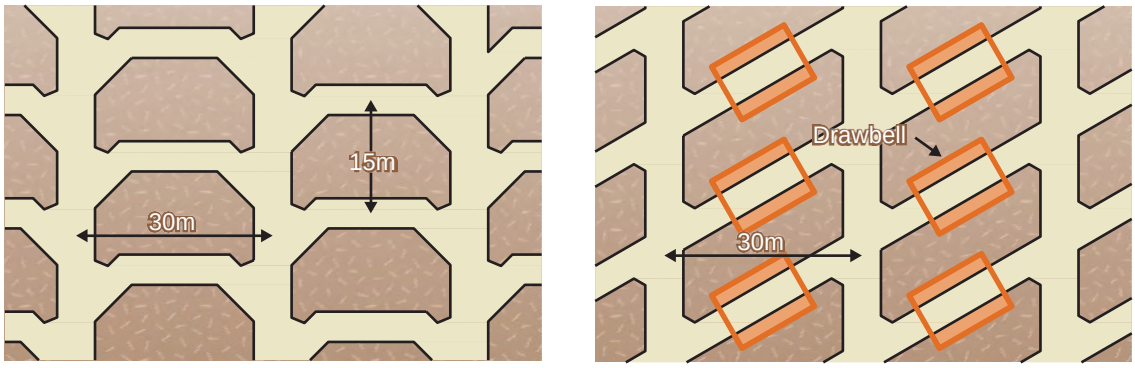


Figure 14: Typical Offset Herringbone (left) and El Teniente (right) Layouts (Laubscher, Guest et al. 2018)

The long-term pillar stability impacts the recovery of the targeted ore. Over time the Major apex is worn away as the material flows through the drawpoint. Drawpoint brow wear narrows the base width whilst the erosion of the tip of the apex affects the height of the pillar. This resulting reduction in the pillar dimensions impacts the load bearing capacity of the pillar over time and leads to convergence and even failure of the pillar prior to the targeted extraction of material from the drawpoint. Many large-scale operations make allowances for a Recovery Level to enable the full extraction of the ore block following the failure of the original Extraction Level. This erosion of the Major apex pillar is one of the key factors which limited the draw height in traditional Block and Panel caving operations in poor or highly fractured rockmasses.

As caving has been applied to more competent rockmasses the final pillar dimensions have enabled higher draw heights to be extracted as the wear impacts are able to be accommodated. These stronger rockmass caves have however seen issues during the cave establishment phase with the dynamic stress loads applied during undercutting and cave propagation. These dynamic stress changes in stronger rock masses have led to rock bursts and other seismic energy release type failures.

During the dynamic loading phase of the cave the risk of rock burst is heightened in areas where contacts between different rockmasses exist. This area is being better understood (Talu, Savage et al. 2016) and modelling tools are being developed to assist geotechnical and mining personnel to predict seismic event prone areas and to design adequate support systems and management plans to keep the workforce safe and improve the integrity of the underground development.

2.3 Undercut and Extraction Level Design

2.3.1 Key Findings

With the introduction of rubber tyred Load Haul Dump (LHD) units in the 1970's the design of the Extraction Level underwent a revolution to accommodate the new technology. The largest change was the reorientation of the drawpoint drive to accommodate the turning capability of the LHD. In the early caves the drawpoints were located perpendicular to, or above, the slusher trough (Weston 2016) as the LHD could not navigate this angle efficiently the turning angle was adjusted to between 50 and 60 degrees. This reorientation resulted in the drawpoint brow being aligned oblique to the drawbell and the associated undercut.

The new layouts, Herringbone and El Teniente, designed to utilise the LHDs also required a redesign of the drawbell (Laubscher 2000). This drawbell redesign incorporated the activities required to establish it, including rise mining, production drilling and charging and brow infrastructure installation. The El Teniente mine in Chile devised a layout to enable dual direction tramming in the Extraction Drive to internal orepasses and to be established with a Post, or Conventional, undercut. A similar footprint was also developed at the Henderson Mine in Colorado, though it was abandoned in favour of the El Teniente version. Due to the bidirectional tramming the drawbell was rectangular in shape and resulted in a four-way intersection as the drawpoint development was aligned to maximise the use of straight lines (Figure 14). As this layout was implemented in a Conventional undercutting sequence the drawbell was established first. The undercut associated with this layout was generally a flat one, level with the height of the undercut drives, and fired down into the drawbell void (Figure 21).

The Herringbone and Offset Herringbone layouts resulted in a drawbell which was larger on one side than the other (Figure 15), this affects the flow of material in the cave. This layout was generally installed in an Advance or Pre-Undercutting sequence which has the undercut fired first and then the drawbell is fired beneath the broken undercut. To overcome issues associated with firing narrow flat undercuts in a confined environment the undercut design was modified to include inclined holes (which also increase the height of the Major apex pillar), sometimes in combination with flat holes above the drawbell (to limit the height of the drawbell) in a style that became popular and known as the "crinkle cut" (Brown 2007). With the drawbell being established under the already fired undercut the execution steps in the drawbell had to account for the rilling in of material from the undercut before the drawbell was fully formed, thus leading to confined blasting for most stages during the

opening.

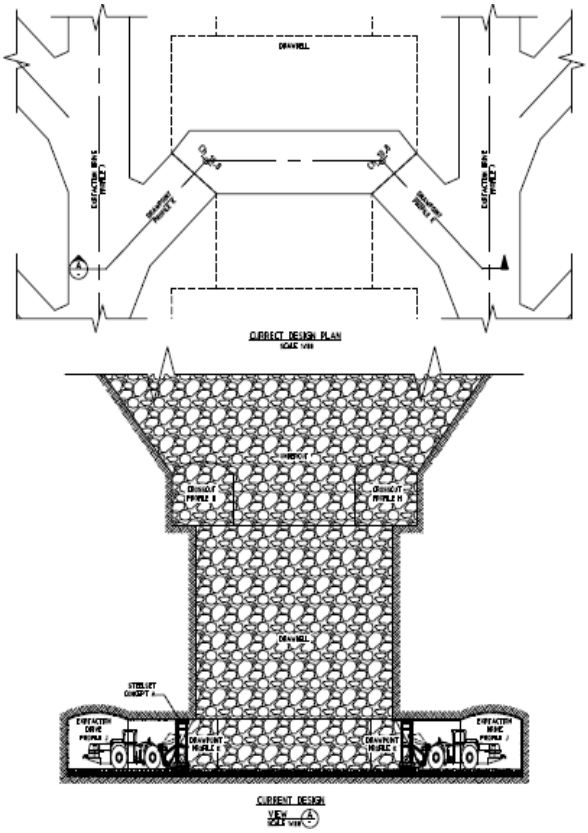


Figure 15: Offset Herringbone Drawbell

The dominant undercut styles were the flat and crinkle cut, though there were also a number of others experimented with by various mines, including a double Sub Level Cave (SLC) style option at Northparkes (Vink 1995) as shown in Figure 16. The undercut geometry (Figure 17, Figure 18, Figure 19) defines the height of the drawbell, the dimensions of the Major apex pillars and the amount of blasted material to be extracted during establishment.

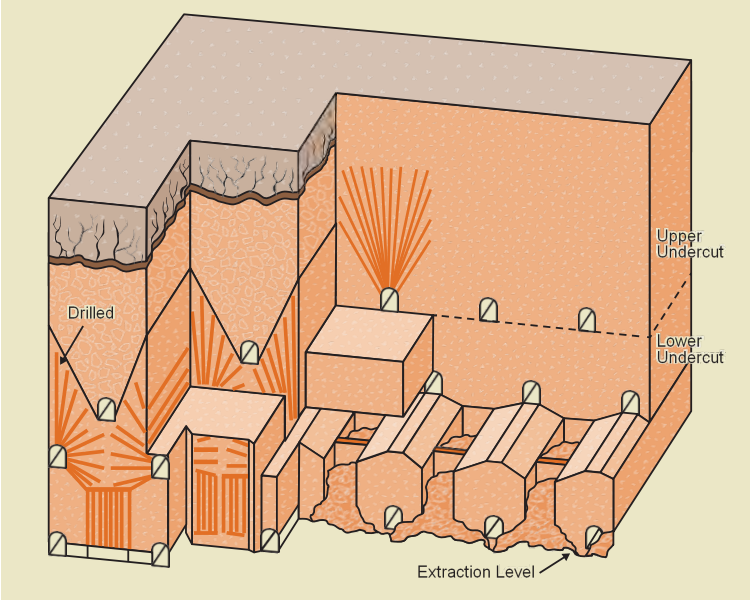


Figure 16: Northparkes Double Undercut (Vink 1995)

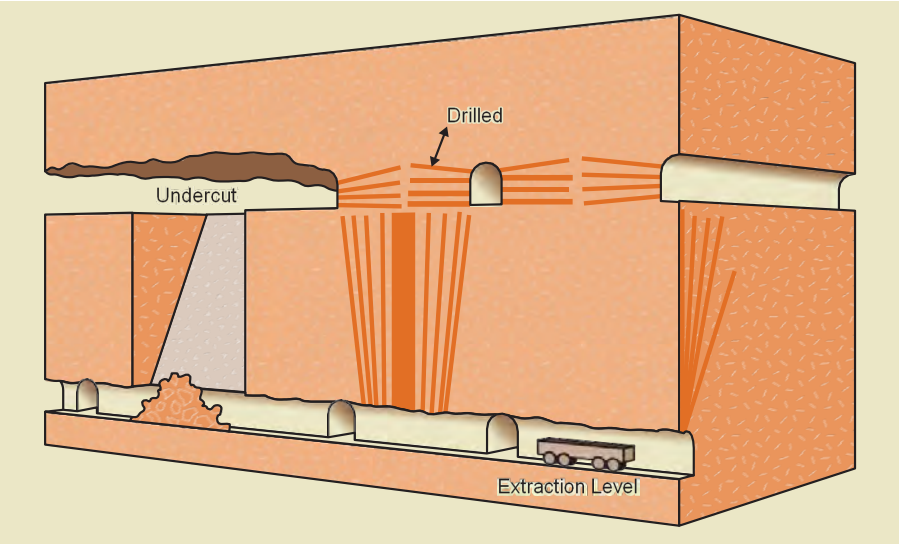


Figure 17: Flat Undercut

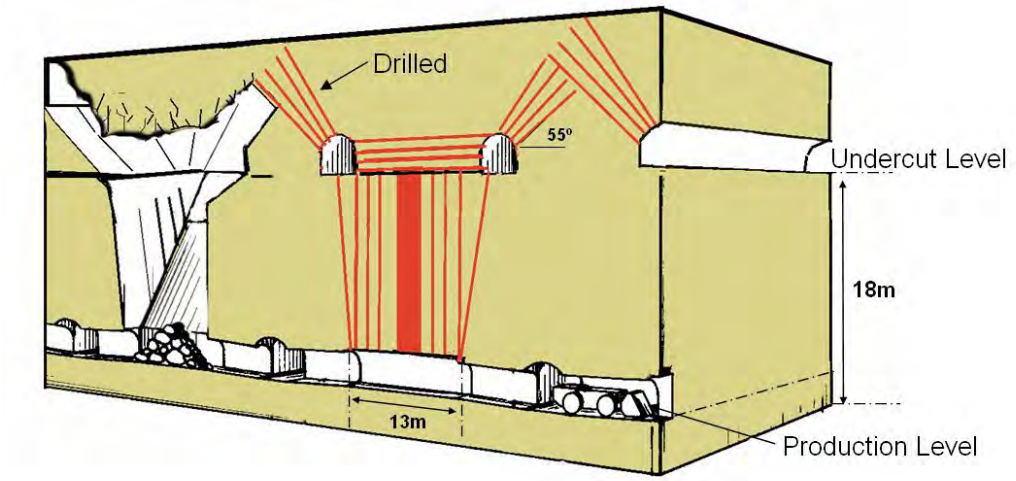


Figure 18: Drawbell established under an Advanced Crinkle Cut Undercut at Palabora (Calder, Townsend et al. 2000)

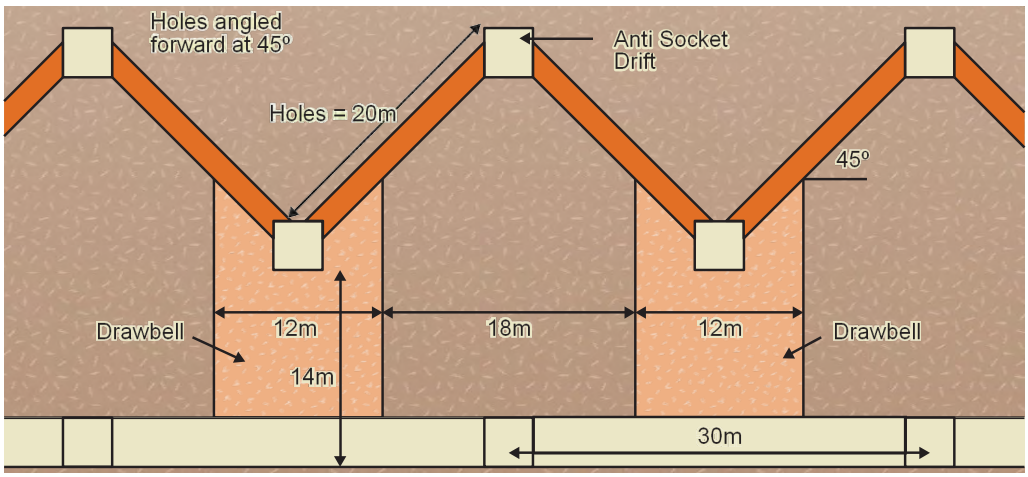


Figure 19: Big W undercut (Laubscher 2000)

The dimensions of the drawbells were limited to the capabilities of the drilling and charging equipment and the sequence of establishment (Figure 20). This led to a drawbell geometry that was based on the dimensions of the Extraction and Undercut Levels rather than the requirements to maximise ore recovery through flow and fragmentation. Even with the utilisation of electronic detonators to enable the firing of the entire drawbell in a single blast the shape of the drawbell has effectively remained the same for the Herringbone and El Teniente designs. The only exception to this is Cadia East which utilised a circular topped drawbell and integrated multi-stage undercut firing to establish an El Teniente layout in a post undercut sequence (Figure 22).

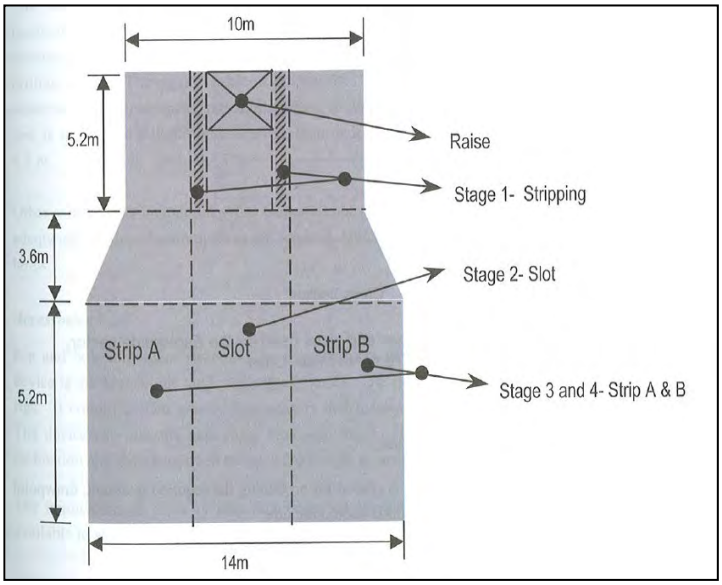


Figure 20: Sequence of establishing an Offset Herringbone drawbell (Brown 2007)

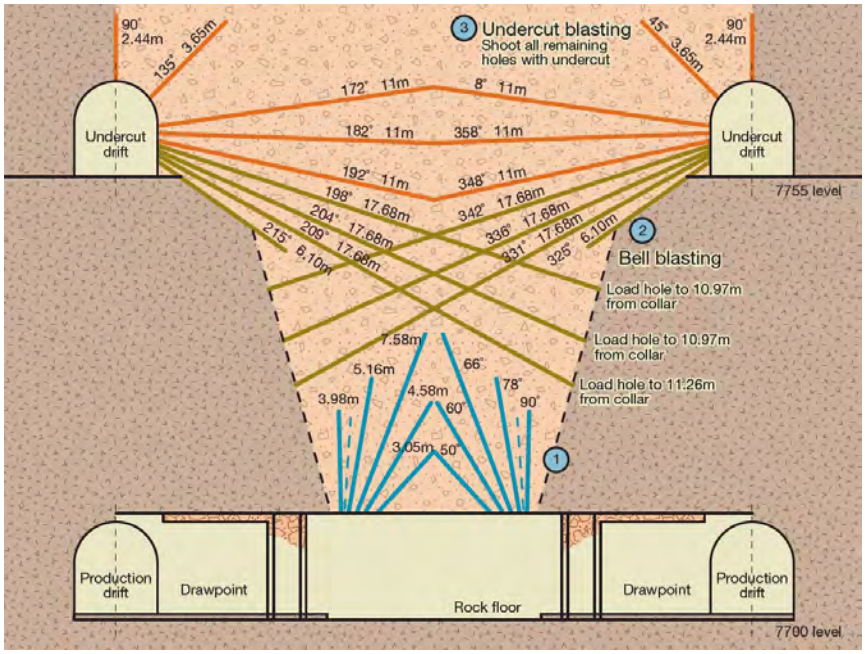


Figure 21: Drill layout for undercutting and drawbell blasting, Henderson Mine, USA (Rech, Keskimaki et al. 2000)

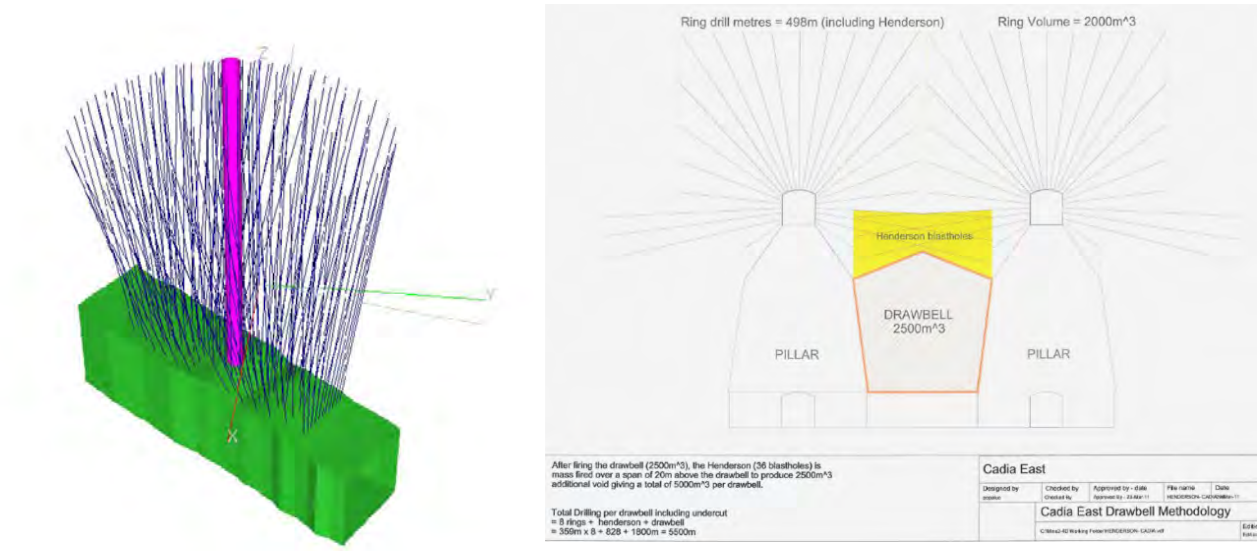


Figure 22: Cadia East PC1 Post Undercut Drawbell and Sequence

A key production constraint identified by (Encina 2008), (Orellana 2016) and (Le-Feaux 2021), was the LHD itself and the under utilisation of the drawpoints available on the level due to the batch nature of production with an LHD. To improve the productivity of the LHD the following have been assessed

- angle of the drawpoint drive relative to the Extraction Drive,
- the depth of the drawpoint brow and rill run out length,
- the tramming path to the tipping location and how many changes of direction are required,
- fragmentation impacts on loading times in the drawpoint, hang up frequency and blockages at the dumping point.

(Encina 2008) investigated a continuous loading system from multiple drawpoints at once to an armoured conveyor located in the Extraction Level. Whilst the system had high instantaneous performance its overall effectiveness was reduced due to high maintenance requirements.

2.4 Flow in Cave mines

2.4.1 Key Findings

The basis of current industry thinking and the computer flow codes used to simulate the expected draw from a drawpoint is based on 2-dimensional scale models as shown in Figure 23. (Power 2004, Castro and Truman 2008) established a 3D model at various scales to simulate flow in a block cave environment though they encountered issues with similitude. There have been some full scale mine marker trials (Brunton, Lett et al. 2016) though the analysis of the results is preliminary at this stage. Most of the scale modelling approaches represent the movement of material in 2 dimensions, the exception being the work initiated by (Power 2004). Thus, the results are not directly attributable to flow on an Extraction Level. The simplification of the complicated and chaotic nature of flow to a 2-dimensional width which is then used to define a draw circle ignores key drawbell geometry and loading equipment impacts as highlighted in Figure 24 and Figure 25. This incorrect simplification though is the basis of the empirical and computer tools used by mine planners to effectively lay out an Extraction Level to maximise ore recovery of multimillion, even multibillion, dollar mines.

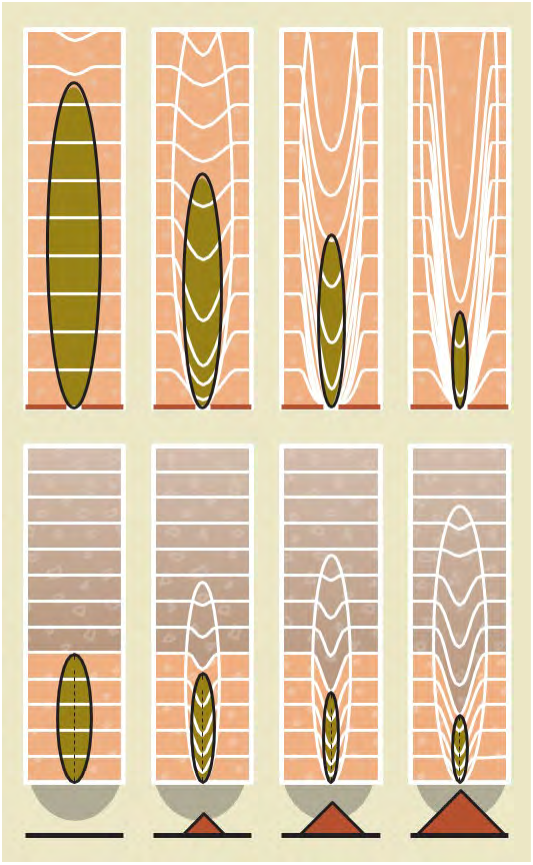


Figure 23: Sequence of drawing material from a single drawpoint (after (Kvapil 1965))

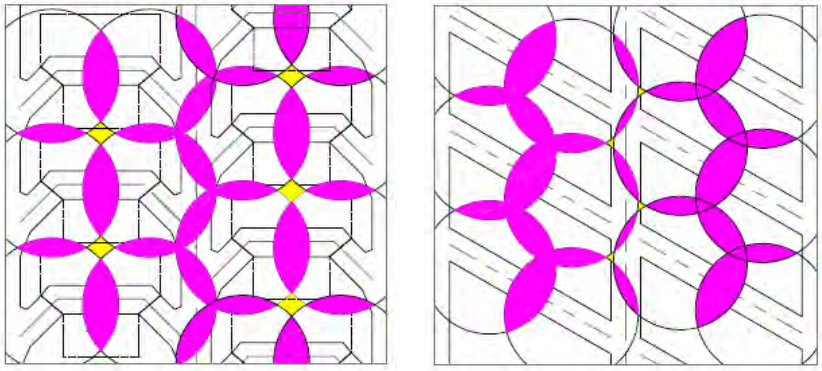
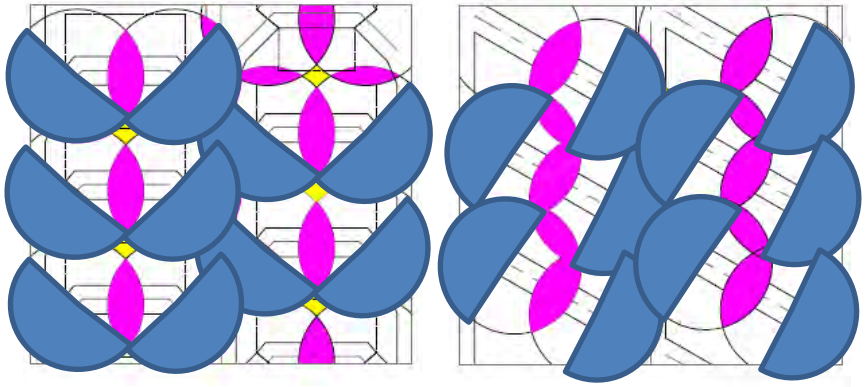


Figure 24: Offset Herringbone and El Teniente layouts with simple draw circles (Dunstan)



Blue shaded areas indicated shadowed draw created by the drawpoint brow location

Figure 25: Offset Herringbone and El Teniente layouts with revised draw envelopes (Dunstan)

Flow is a three and almost four-dimensional problem. The depth of penetration into the muckpile, and therefore influencing the movement inside the drawbell is critical to understanding the interaction of the drawpoints on either side of the drawbell. The 4th dimension (time) plays a factor in understanding the influence of compaction on the movement zone material. The literature (Kvapil 2008) indicates that the volume of the movement zone is potentially 15 times larger than the volume of the extraction zone. As current knowledge in the industry advocates drawing evenly from across the footprint to induce a level drawdown of the ore and defer the ingress of waste, this phenomenon of compaction plays a role in how often a drawpoint must have material extracted from it to keep the cave column mobile and the draw columns interacting with each other. The timing of compaction of the draw columns also influences the load carrying capability of the ore columns and the degree of cave weight which will be placed on the Extraction Level pillars.

There has been some discussion (Brunton, Lett et al. 2016, Koch 2022) that the near field flow, within 70m of the drawpoint brow, is heavily influenced by the integrated shape and blasting of the drawbell and undercut and also the undercutting sequence (Advance (Figure

26) or Post (Figure 27)) and is not necessarily aligned with the theoretical draw ellipses identified in the 2-dimensional scale models. The near field draw appears to be influenced by the finer and more mobile blasted material than the coarser, unblasted cave back material which is relying on gravity to mobilise it. Brunton theorises that when firing an Advance undercut sequence using a crinkle cut undercut and Offset Herringbone drawbell design, the coarser cave back material above the flat section of the undercut, directly above the drawpoint, is delayed in entering the drawpoint as the finer material associated with the inclined undercut holes used to shape the Major apex flow in preferentially and then skews the near field draw to be above the Major apex rather than directly above the drawpoint. Over time the coarser material above the drawpoint breaks up and is recovered. This phenomenon was not observed when a Post undercut strategy was used with a modified High undercut over an El Teniente drawbell layout, as the blasted undercut left a horizontal undercut shape. The flat undercut resulted in a consistent cave back fragmentation and the integrated undercut and drawbell geometry channeled the material to the drawpoint resulting in a more theoretical recovery geometry.

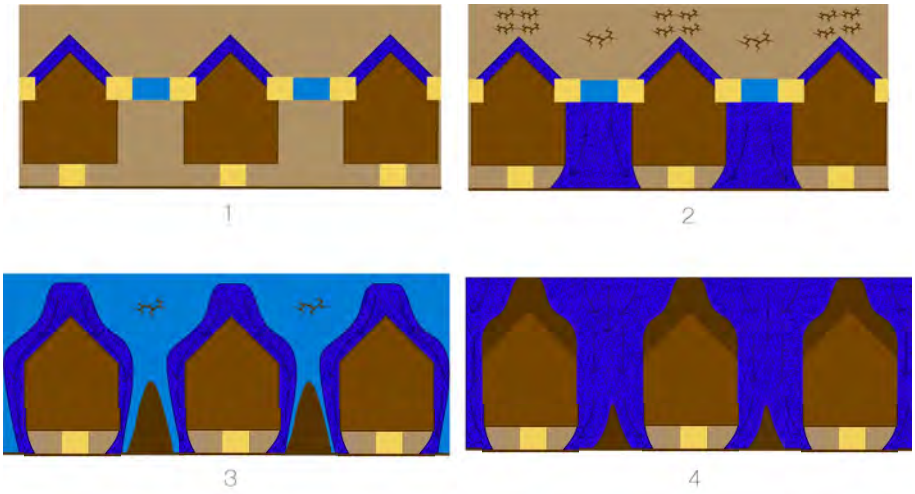


Figure 26: Advance Undercut flow zone stages (Dunstan)

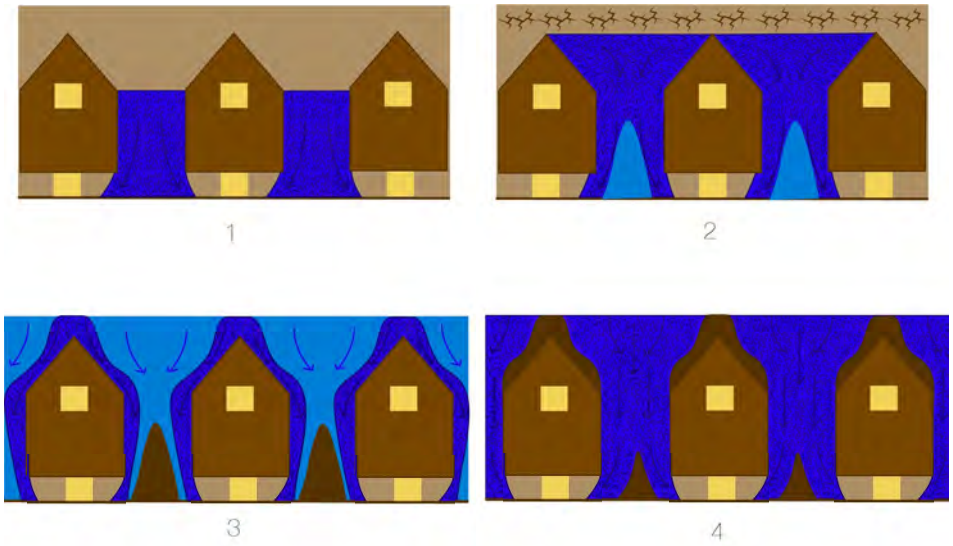


Figure 27: Post Undercut flow zone stages (Dunstan)

The width of the draw zone is related to the fragmentation in the cave column. The finer the fragmentation the narrower the draw column and the coarser the fragmentation the wider the draw column. This has been observed in laboratory scale (Sharrock and Hashim 2009) and mine scale (Brunton, Lett et al. 2016) tests. (Sharrock and Hashim 2009) proposed a Disturbed Extraction Zone (DEZ) to account for the interlocking of particles which then changes the flow zone dimensions. Under the DEZ criteria the interlocking of finer fragmentation would see them behave in a similar way to coarse fragments and therefore increase the effective draw width achieved. Full scale experiments conducted at Newmont's Cadia Valley Operations (CVO) support the theory that the actual horizontal draw width is wider than previously predicted (Brunton, Lett et al. 2016). Follow up work by (Paredes 2022) identified that in the more competent rockmass caves at CVO, and in laboratory experiments, the draw zones became wider and there was limited ore loss associated with the wider drawpoint spacing when the column heights were increased.

Defining the width of the draw zone is a critical design component when laying out the spacing of the drawbells and ultimately assessing the potential recovery from a targeted ore block. The spacing of the drawbells determines if there will be interaction between the movement zones created at each drawpoint. If the drawpoints are spaced wider than the movement zones of adjacent drawpoints then isolated draw will occur with limited ore recovery and likely stability and cave propagation issues. (Laubscher 1994) proposed that the drawpoints should be placed 1.5 times the diameter of the estimated draw zone as this would ensure that the material between the draw zones would collapse and therefore create an expanded draw zone from the 2 drawpoints in a drawbell (Figure 28). This would then continue where the material above the Minor apex, between the adjacent drawbells, would yield and subsequently result in a larger draw zone along the alignment of the adjacent

drawbells. This is then repeated over the Major apex where the enlarged drawzones of the adjacent drawbells on either side of the extraction drive result in the collapsing of the arches formed above the Major Apex thus ensuring full movement of cave material above this point, which he called the Height of Interaction (HIZ).

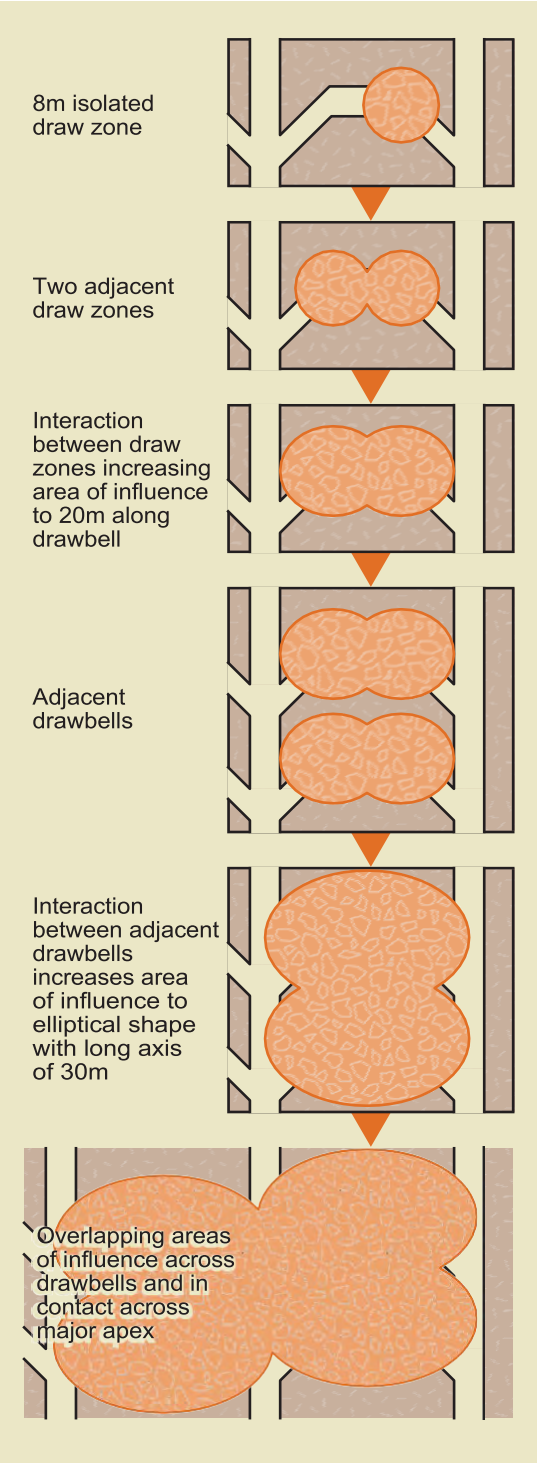


Figure 28: Progressive development of the draw zone interaction in adjacent lines of drawbells (Laubscher, Guest et al. 2018)

Dr Pierce, (Pierce 2010), in his PhD stated that:

"The shape of the Isolated Movement Zone (IMZ), particularly the maximum width, and the distribution of velocities internal to the IMZ and how these are impacted by the properties of flowing material is critical to the design of adequate drawpoint spacings. Caved rock and caving environments exhibit characteristics that can differ significantly from the conditions in silos and hoppers (where the majority of flow research has been undertaken)."

Pierce focused his research on the following behaviours;

- IMZ width and internal velocity distribution associated with flow above a single isolated drawpoint. Also considering the impacts of a mixture of material types and free surface rilling which can occur below a stalled cave back or ground surface leading to rapid lateral migration
- Overlap of IMZs above multiple drawpoints and the associated potential for uniform drawdown. Caves generally contain numerous drawpoints which are drawn in successive, incremental and often non-uniform fashion
- The potential for stress driven flow of stagnant zone material prior to the development of overlap (interactive) draw
- Secondary fragmentation and the impact of the size of rock fragments decreasing over time as the cave matures. As secondary fragmentation causes the mean fragment diameter to decrease with draw/time, this can have impacts on IMZ shape and fines migration
- Fines migration as there is evidence to suggest that finer fragments of cave rock can migrate more rapidly through the cave than coarse fragments. This is important as it leads to preferential influx of finer waste material (e.g. previously exhausted cave level) located above the column and local accumulations of fines that can flow unexpectedly particularly in the presence of water

Pierce also undertook an assessment of the various flow code types, Stochastic, Kinetic, Empirical, Rapid Emulation Based On PFC3D (REBOP), and their applicability.

The velocity profile within the IMZ, based on a review of available data varies under the following conditions:

- When the IMZ width is less than 20-30 mean particle diameters the velocity profile is characterized by two shear layers (each 10-15 particle diameters thick) and takes the form of an inverted triangle in two dimensions – maximum at the centreline and decreasing in an approximately linear fashion to zero at the IMZ limit. See left diagram in Figure 29.
- When the IMZ is greater than 20-30 mean particle diameters, a central plug-flow

region develops between the two shearing layers, occupying the central portion of the velocity profile (Figure 29 right). The width of the central plug-flow region is equal to the difference between the total width of the IMZ and the combined width of the two bounding shear layers.

- Horizontal velocities have been noted in experiments and simulations, they are greatest near the angled base on the IMZ where particles must move radially towards the draw orifice in order to exit. They also exist higher in the IMZ, where continuity requires that new particles entering the movement zone and dilating must move toward the centre of the IMZ
-

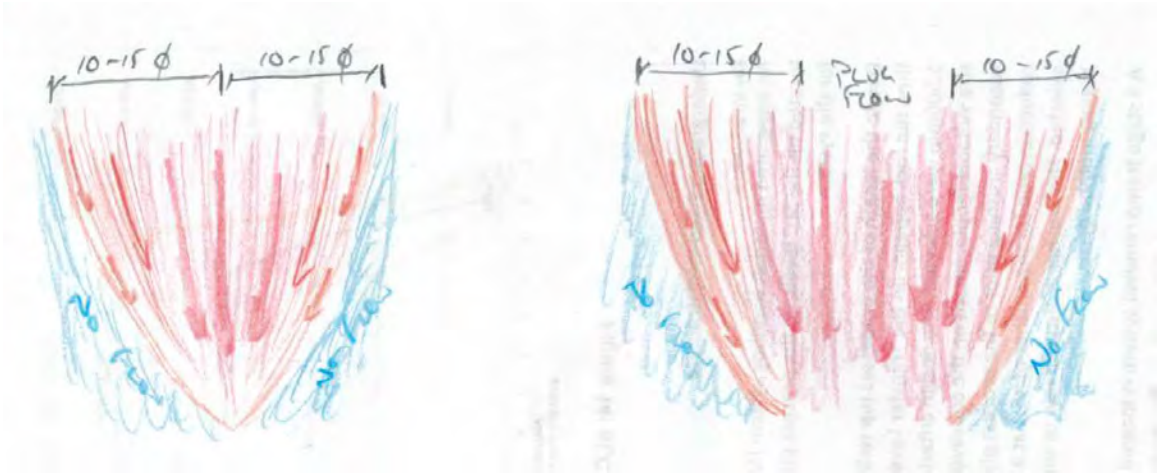


Figure 29: Flow velocities for less than 30 particle diameters (left) and greater than 30 particle diameters (right) (Dunstan)

Secondary fragmentation (Figure 30) within caving is commonly attributed to a combination of splitting (bulk fracture or crushing) and rounding (abrasion) that occurs as rock fragments travel from the cave back to the drawpoints. A review of stress and strain conditions within the cave suggest that it is logical to consider secondary fragmentation under conditions of compression and shear, which broadly characterises the conditions in the stagnant zone and IMZs, respectively.

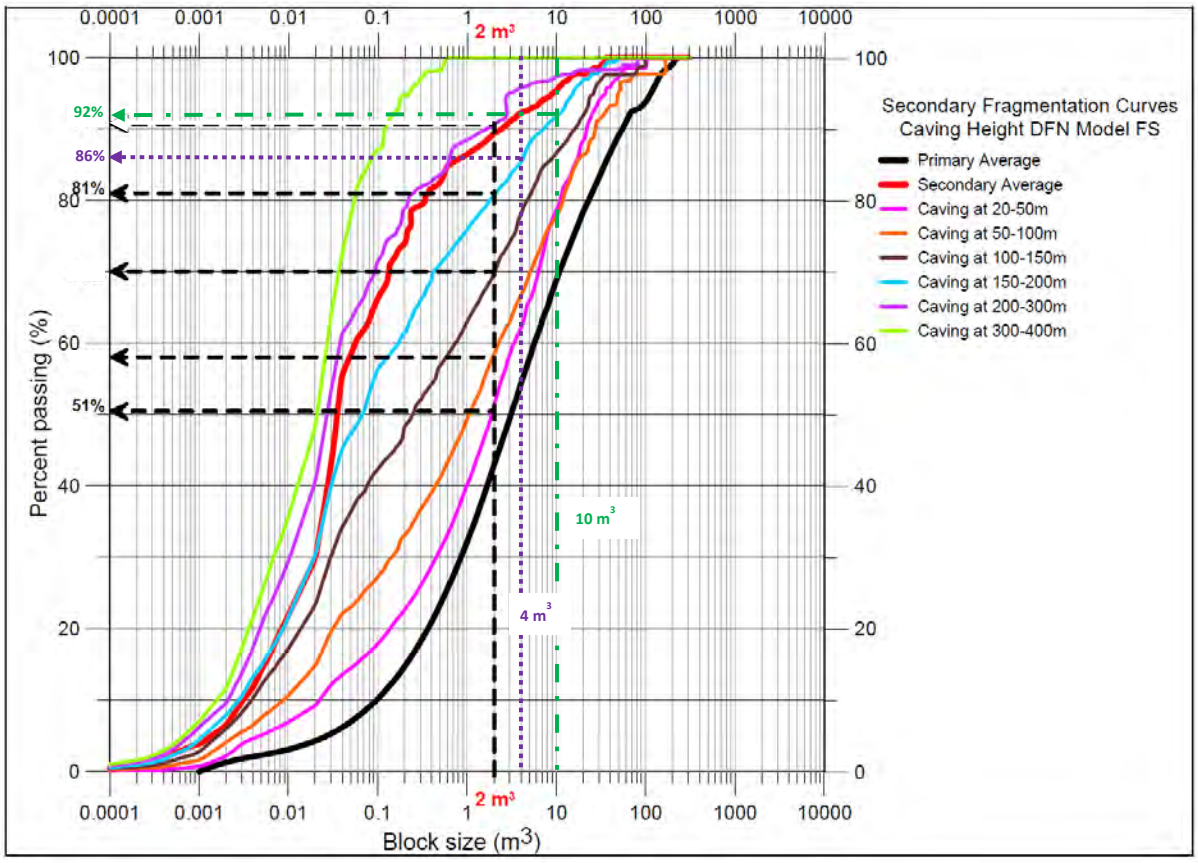


Figure 30: Secondary Fragmentation Curves by height for Cadia East PC1 (personal communications)

There are many key factors that are likely to control secondary fragmentation in caves, including shear strain, stress, shape, size distribution, strength and initial porosity.

(Bridgwater, Cooke et al. 1978) described fines migration as a release-capture process in which a percolating particle travels downward through layers of larger bed particles in discrete steps. The ratio of percolating particle diameter to bed particle diameter (diameter ratio) was found to have the largest effect on percolation rate (Figure 31). Simulations indicated that when fines are traveling with the coarse bed particles they move both laterally and vertically. When percolating, however, they tend to move only vertically. Where the IMZ narrows near its base, this can lead to a stagnation of fines. As they percolate closer and closer to the IMZ limit, it appears possible for the fines to migrate out of the IMZ entirely. The percolation rate is sensitive to the strain rate.

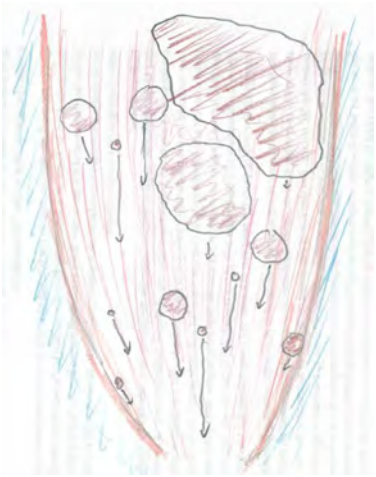


Figure 31: Relative velocities of particle flow within the Movement Zone (Dunstan)

Most of the information relating to flow is from shallow caves less than 1,000 metres below the surface. As the industry is now caving at depths greater than 1,000 metres some of these observations are no longer relevant. Additional impacts to be considered at depth include ore loss, cave loading and increased fines generation due to the increased cave propagation and ore column heights as the vertical separation between footprints is also increasing.

Since the 1990s cave flow computer models have been evolving from simplistic stochastic flow and particle mixing models to cellular automata models including cave shape impacts constraining flow and rilling of material inside the cave to integrated cave growth and flow modelling including air gap prediction and the latest models are utilising physics-based flow codes (Figure 32).

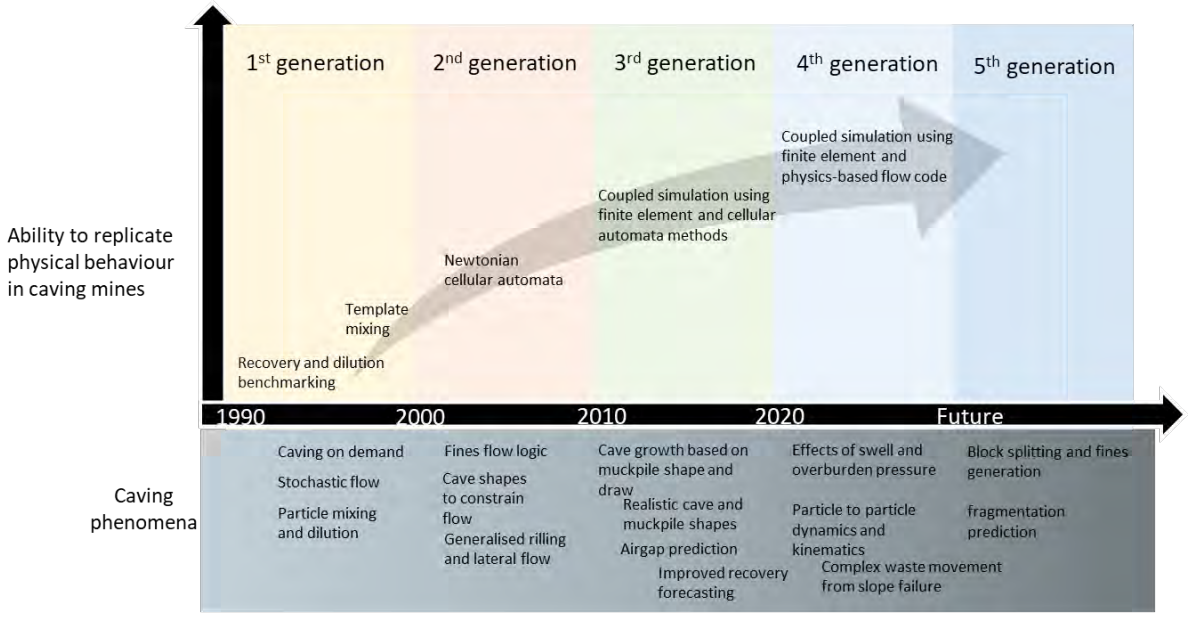


Figure 32: Computer Cave flow code evolution (after (Beck Engineering 2021))

As the cave column heights are increasing so is the importance of understanding the

relationship between the cave back and muckpile geometries. Most caves prior to 1990 were in relatively poor ground conditions, kimberlite pipes and secondary ores, at depths less than 800m and had a column height of ~200m and a minimum span resulting in a <1:1 height to width ratio that led to near vertical cave walls, constrained by geological features, and limited footprint life. Since the 1990's and the implementation of the Block Cave method in more competent rock masses, predominantly to extract Porphyry style deposits, the caving heights have increased from 400m to ~1,300m as mining companies look to increase the economic benefits of the method by limiting the number of Extraction Levels in a vertical deposit. This increase in caving height and subsequent increase in the height:width ratio changes many of the initial assumptions relating to cave propagation and flow which pushed the industry to try and understand the relationship between cave propagation, muckpile height and ore block recovery. In simple terms the adage of establishing a flat back cave to maximise ore block recovery becomes increasingly challenging at depth. The Cave initiation sequence and geometry plays a critical role in the cave propagation geometry which is predominantly an arch with the crown of the arch approximately midway across the active footprint area (Figure 33). This arching phenomenon results in cave back material not necessarily presenting vertically above the active draw points and with the arched cave profile restricting vertical flow, there is a rilling affect as material from higher sections of the muck pile cascades across to fill in the draw requirements of the edge draw points sitting directly below the lower sections of the arch. This rilling phenomena influences not only the ultimate shape of the cave back but also the internal flow and ore recovery of the higher ore block. The higher the targeted ore block and ultimate cave geometry the greater the risk of ore loss due to arching as the lower sections of the cave back are essentially buttressed by broken material and the cave back span is restricted, thus reducing the likelihood of natural caving occurring in these areas.

Draw strategies with strict compliance are used in the cave establishment phase in an attempt to maintain the shape of the cave back and limit the influence of material rilling. With deeper and larger footprints which are often started in the weaker material to assist caving, these draw strategies do not always overcome the cave back arching phenomenon.

To further overcome this arching phenomenon mining companies have invested in preconditioning methods in an attempt to engineer the rock mass to ensure the targeted ore is fractured and will yield under the desired cave shape and when this might not occur the opportunity exists for postconditioning which involves hydraulically fracturing or blasting the edges of the cave which haven't propagated satisfactorily and attempting to generate the desired caving shape.

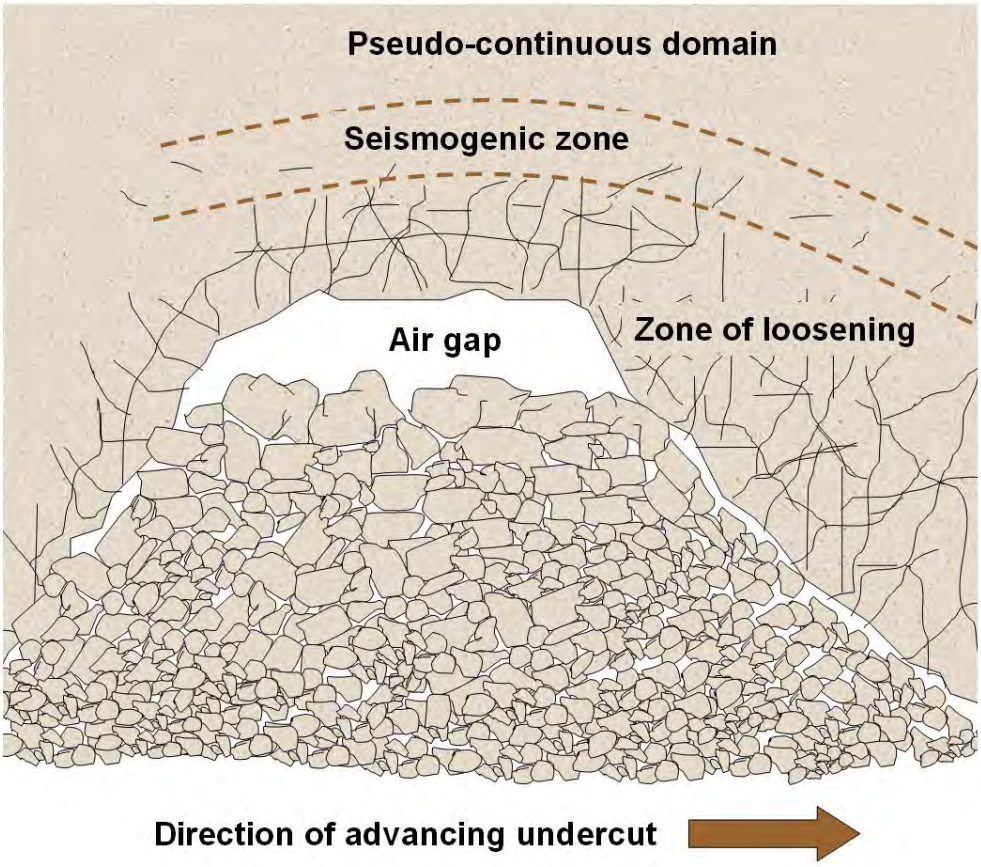


Figure 33: Conceptual model of caving (after(Duplancic and Brady 1999))

As caving footprints increase in depth and cave column heights increase, this establishment of the cave footprint at the desired spans to ensure ore block recovery becomes more and more critical. The evidence suggests that whilst preconditioning utilising hydraulic fracturing is advantageous for stress redistribution and potentially particle size reduction, it does not play a part in determining the boundaries of cave propagation. Postconditioning is identified as the preferred option for generating the desired cave shape if the cave shape has not been achieved through managing the initial cave propagation and draw strategy.

Fragmentation plays a considerable part in the flow and recovery aspects of all columns. It is understood that coarse fragmentation will lead to wider draw columns and that finer fragmentation will lead to narrower draw columns and the finer fragments will move at a greater rate through the ore columns. The desired fragmentation sizing is a trade-off between the fragmentation distribution that will lead to achieving the desired movement and extraction zone column widths but also the fragmentation distribution which will ensure minimum production interruptions to the Extraction Level materials handling system. The size of the draw points and the shape of the drawbell will influence the near field draw column parameters and will also determine the maximum particle size which will present

at the drawpoint. The spacing of the drawbells influences the far field draw performance through the interaction of the individual draw and movement zones of the cave material.

2.5 Extraction Level Operating Strategies

2.5.1 Key Findings

The operating strategies of an Extraction Level are based on maximizing the safety and productivity of the mine.

To achieve the requirement of consistently drawing from all drawpoints, the ultimate production rate of the Extraction Level is determined by the productivity of the drawpoint(s) with the longest travel route to the materials handling system (Mariager 2024). The materials handling system in this context is either an on-level crusher, an orepass system or truck loading area (Pratt 2008).

Many of the larger operations (El Teniente and Henderson) rely on internal ore passes to limit the tramming length of the LHD. The orepasses are located along the Extraction Drive and usually involve excavating into a pillar to allow the dumping of material and extend to a Haulage Level some 30 to 50m below the Extraction Level. The El Teniente mine developed a layout to accommodate the in-footprint orepasses and which allowed the LHDs to travel in both directions in the Extraction Drive to enable dumping in the nearest orepass. Whilst these orepasses reduce the tramming length for the LHDs they come with the compromise on footprint stability, constructability and maintainability of the level and requirement for finer fragmentation from the cave due to the size of rock they can accommodate (this leads to a large increase in the amount of oversize material which needs to be treated both on the Extraction Level and in a dedicated intermediate rock breakage level between the Extraction and Haulage levels). Over time, as the LHD capacity has increased, the fragment size which can be successfully fed through the orepass has had a limiting effect on the productivity of the mining blocks.

The on-level crusher design began in the early 1990’s on footprints utilising the Herringbone or Offset Herringbone layout, mines utilising this design included Northparkes E26 Lift 1 and Palabora. This configuration allowed for larger fragmentation to be drawn and tipped in the crusher than traditional caves, using the in-footprint orepass system, as the crusher could accommodate the coarser material. The layout also allowed the use of electric trailing cabled LHDs and automation of loading activities to improve the operating environment in the caves as the LHDs only needed to travel in one direction to access the drawpoints. The downside of the design was that the tramming route for the LHDs was increased as the crusher(s) had to be located in a safe area outside the influence of the abutment stresses generated by the cave, in the order of 50 to 75m outside the production

area. The cost of the crushing stations also influenced the number installed and the trade-off between tramming distance, production rate and capital cost would be used to determine how many were installed per mining block.

Due to the production efficiency gains in being able to discharge larger fragments directly to the crusher and the improvements in LHD design the current state of the art mine layout for a Block Cave is to utilise the El Teniente layout with an on-level crusher for approximately every 8 extraction drives (Cadia East style). By feeding the crusher with multiple loaders the tramming length can be balanced out, though it is still more than those footprints which utilise the in-footprint orepass system.

Due to the complex and interlinked nature of the activities required to successfully operate a block cave mine, the scheduling and management strategies are crucial to the successful operation of the mine. The list of activities required to be coordinated includes, but is not limited to:

- Production loading,
- Drawpoint sampling,
- Services inspection and repair,
- Drawpoint inspections,
- Oversize management,
- Hang up treatment,
- Roadway maintenance,
- Geotechnical monitoring, including convergence and ground support investigation,
- Ventilation monitoring and adjustment, and
- Equipment servicing

As the size of the mining footprints and the production rates are increasing there has been an increasing reliance on computer programs to assist the mine operations teams.

2.6 Cave Mine Draw strategies

2.6.1 Key Findings

Whilst there are limited papers published on the draw strategies applied to the extraction of material from Block Cave drawpoints it is a crucial element in the successful establishment, operation and closure of a Block Cave Extraction Level.

(Conejo, Pinochet et al. 2016) outline the approach applied to the El Teniente panel caving footprints to ensure the cave loads are successfully redistributed during cave ramp up and that the targeted ore block is fully broken. (Deiring 2008) explains the need to simplify the approach for the establishment, operation and closure of a level on to a piece of paper rather than letting the computer do the “thinking”, this approach ensures that the caving team understand the reasons behind the draw approach. Draw strategies can also be used to manage wet material in the cave (Samosir, Basuni et al. 2008) and through the mines materials handling system.

(Catalan, Onderra et al. 2017) discuss the potential opportunities of utilising intensive (hydraulic fracturing and blasting) preconditioning of the rockmass to manage the effects of seismicity and improve the drawpoint performance through the reduction in fragmentation size.

In the early stages of establishing the cave, the draw strategies will be used to manage the material between the Extraction and Undercut levels and the airgap to ensure the safety of personnel and infrastructure during cave back propagation, and also to try and steer the cave back, as discussed in (Cuello and Newcombe 2018). Coupled models incorporating cave initiation, propagation and material flow (Beck 2011) have become key to understanding the linkages between cave propagation and draw practices.

During steady state operations the draw strategies are based on maximizing the ore recovered from the target ore block and reducing the amount of dilution (waste) material extracted in the process. It is generally accepted that an even draw from all drawpoints on the level within a given time period (notionally a day, a week or a month) will provide the best ore recovery. The length of the time period will vary from mine to mine and is defined by the number of drawpoints, extraction drives and the setup of the materials handling system and how often the loading unit can get through the desired draw strategy.

The length of the time period can lead to variations in the application of “even” or quasi-

simultaneous draw, as per Figure 34. A balance is required between continual drawpoint place changing and not extracting too large a portion of rock in a single draw cycle.

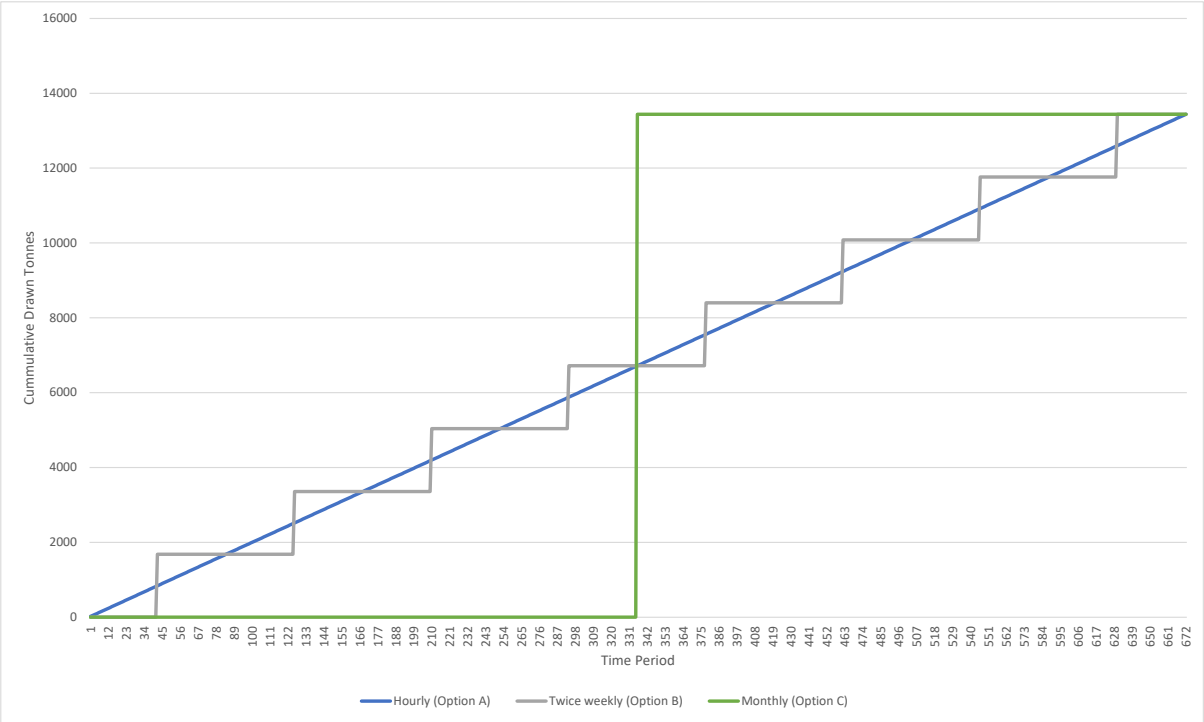


Figure 34: Variable Draw Strategies (Dunstan)

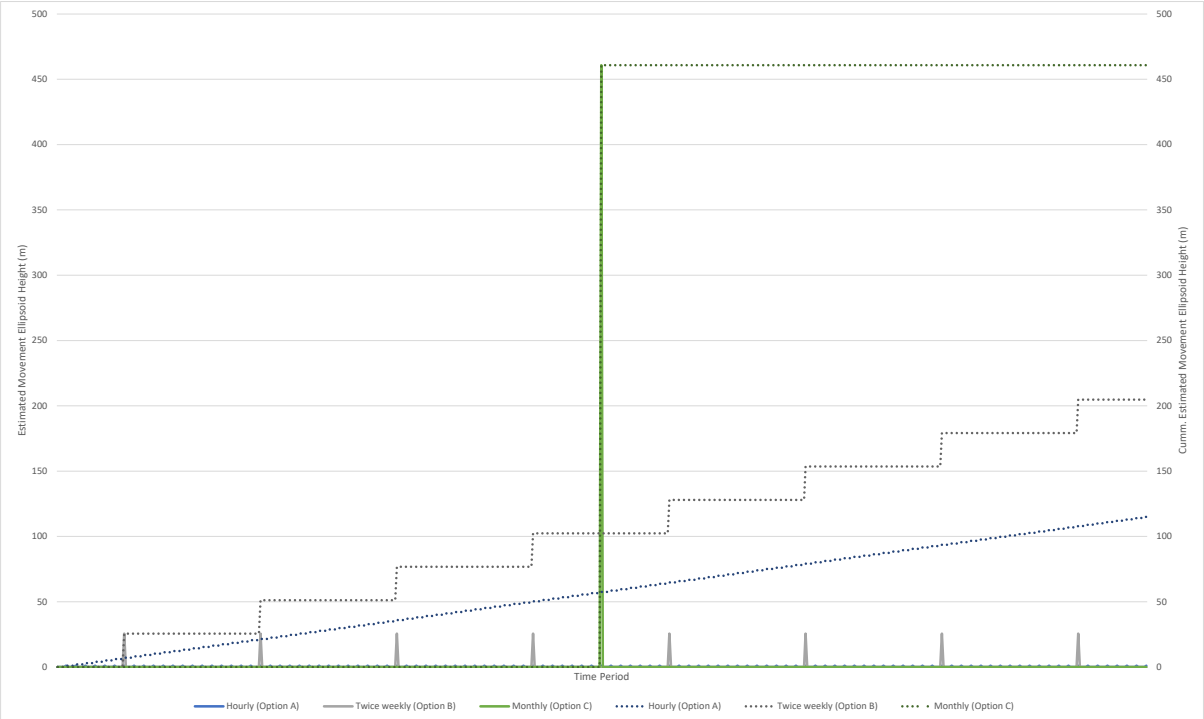


Figure 35: Theoretical Movement Ellipsoid heights for various draw strategies (Dunstan)

As shown in Figure 34 all 3 draw strategies achieve the same total extraction over the nominated time period however Option A is likely impractical and would be highly inefficient with continual place changing. Figure 35 shows the potential impacts on the

extraction height for the various strategies with Option A having the least impact due to the almost continual removal of material from the drawpoint keeping the cave column fully mobilized. Option C is the other end of the spectrum where the period total is extracted in one lot and this can lead to a “piping” of material movement within the larger caving column due to the large extraction in a single event. The preferred strategy is similar to Option B which extracts the desired material in a number of reasonable parcels over the time period, limiting the amount of place changing and ensuring that enough material is extracted to provide movement in the cave column without perpetuating isolated draw and movement zones.

The timeframe between the drawpoint extraction events is based on the compaction timing of the material contained within the cave column. The drawpoints need to be extracted at such a rate that the material within the cave column stays mobile and does not settle or compact as this will influence the extraction and movement zones associated with the drawpoint. The time period also provides a restriction on the duration that a drawpoint can be unavailable, awaiting the removal of a hang up or the rectification of drawpoint infrastructure.

2.7 Conclusions from the Literature Review

Many of the current operating, under construction and under design Extraction Levels around the world are arguably based on outdated knowledge, theories, and equipment capabilities from the literature reviewed and personnel communication with industry colleagues, though some are using the latest modelling techniques for design. The current design methodologies are based on (Laubscher 1994) which was predominantly developed in Africa and Chile in the 1960's and 1970's with limited advancement since.

In the author's view the progression of Extraction Level layouts is reaching another revolution point (Figure 36), as the current Extraction Level layouts utilising LHDs as the primary mode of materials handling on the levels are approaching their limits. The trade-off between the stability of the Extraction Level and the desired drawbell spacing for ore recovery is becoming one that is no longer a compromise with one or both objectives being slightly impacted but rather one where one of the objectives is discarded in preference for the other. Examples of this decision making are Extraction Levels with a designed failure rate of drawbells in a certain section and a Recovery Level being designed, not as a contingency, but as part of the mine plan to enable recovery from the failed zone. These mine layouts generally utilise orepasses from the footprint as they enable the primary crushing units to be located below the Extraction Level and on the Recovery Level elevation so that production rates can be maintained. On the other end of the decision spectrum are examples of mine footprint dimensions being increased to ensure stability of the footprint through larger pillars but this leads to lower ore recovery through inconsistent caving and isolated draw zones.

From the review completed there is a need to develop a new design for Block Caving Extraction Levels at depth which provides both stability and ore recovery to ensure that the mining method is a viable option for the deeper deposits to be extracted in the future.

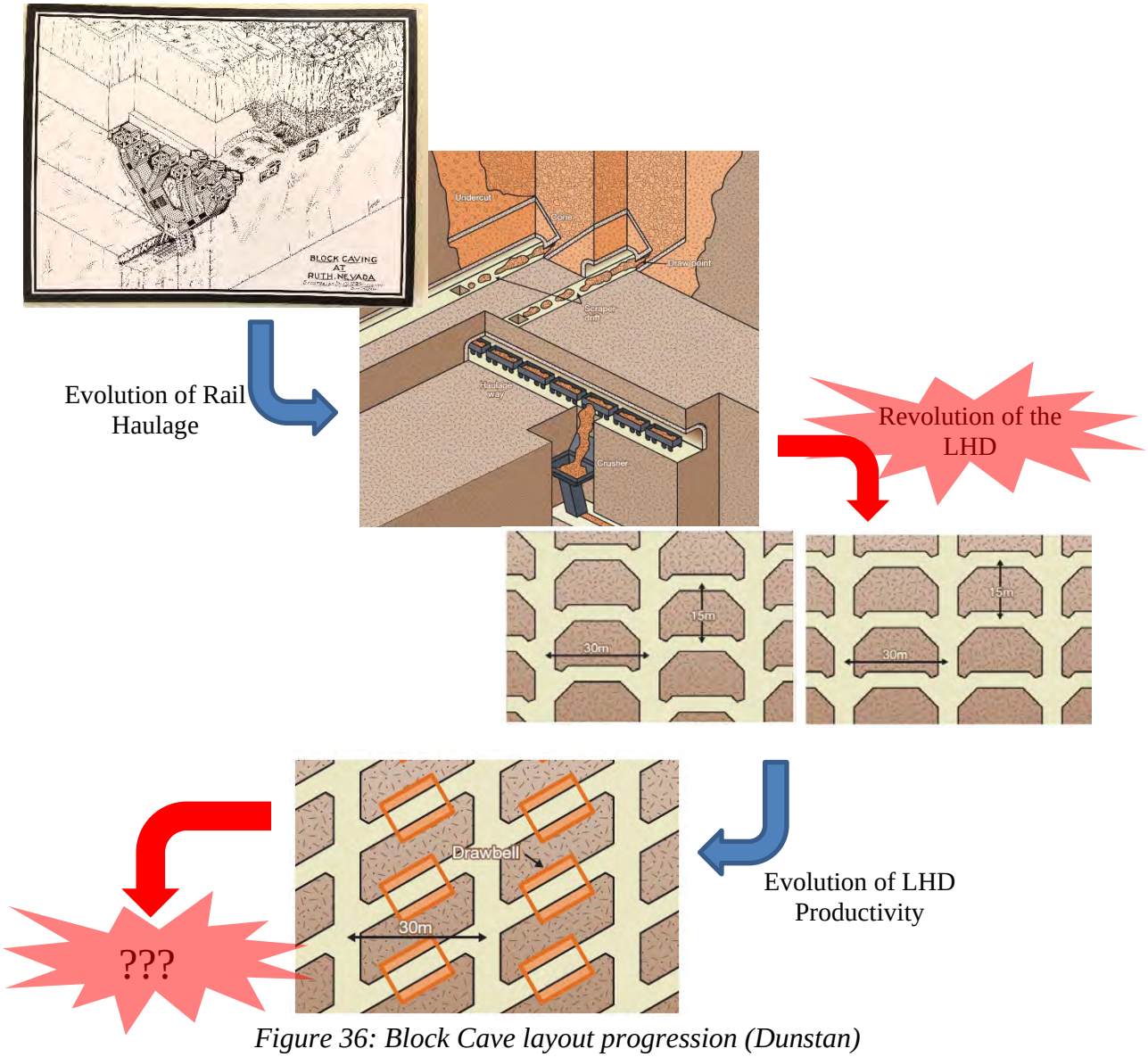


Figure 36: Block Cave layout progression (Dunstan)

To ensure the maximum recovery of the broken material the size of the stagnant zones must be minimized or eliminated where possible. To achieve this the drawbell geometry needs to be at an angle greater than the angle of repose of the material to be drawn and the layout of the drawbells needs to be such that the movement zones overlap (the greater the overlap the higher the opportunity for ore recovery).

The inconsistent fragmentation dimensions and shapes result in a varied extraction zone geometry, in a localized sense, which is chaotic and impossible to predict. As such, it is necessary to simplify the draw geometry to a number of properties which can be modelled in a reasonable time, acknowledging that with the advances in computing power and programming that the opportunity to model more complex draw geometry is increasing. The common programming approaches used in the industry are Stochastic, Cellular Automata, Empirical and Kinetic, though all of them rely on observation and draw markers

for calibration. Numerous field trials have indicated that the geometry of the drawbell and the undercut plays a significant part in the initial flow performance, and that it is not as simplistic as the theory, or engineering drawings, suggest.

The velocity of different particles within the movement zone is important as it impacts the material extracted from the drawpoint. The finer particles are understood to move down through the cave column more rapidly than larger particles. This has been observed from the initial material reporting to a drawpoint as it is opened-up, compared to the material reporting through a mature drawpoint over its operational life. Due to the comminution effects on the particles as they move down through the cave, the fragmentation within a cave column fines up as the drawpoint matures (Figure 37). This change in the fragmentation size also changes the width of the draw column and the influence the extraction of material from a drawpoint has on its neighbouring drawpoints over time. This changing influence results in changes to the stress shedding effects of interacting draw zones and leads to cave weight loading on Major apex pillars and subsequently convergence in the Extraction Level drives.

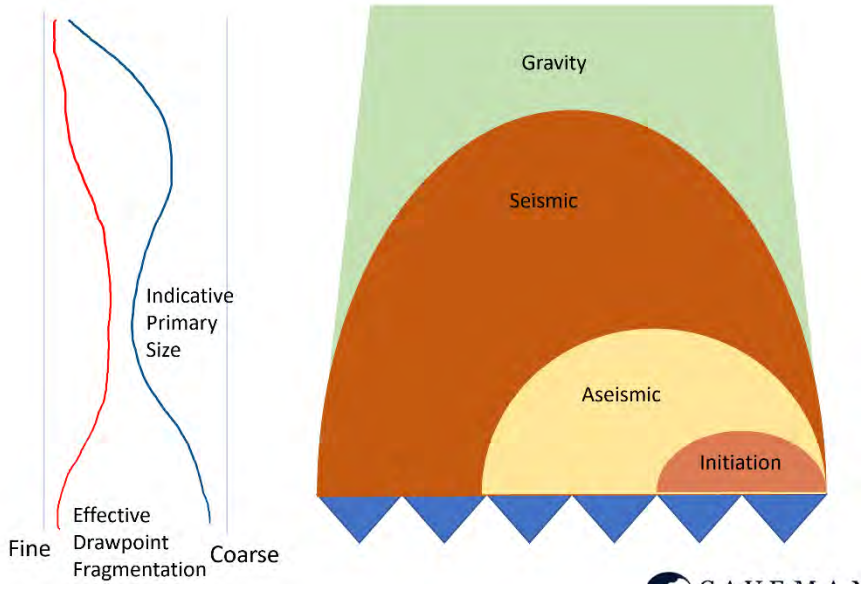


Figure 37: Fragmentation over time

A critical component in establishing a caving footprint is to ensure the successful undercutting of the targeted ore block. This requires a robust and practical undercut geometry, including an integration with the drawbell design and an appreciation of the impacts of the undercutting sequence (post, pre or advance). Post undercutting provides many advantages in terms of undercut firing (larger volumes can be blasted as the drawbell

void is available to blast into, the blasts are not considered confined or choked due to the void available) and determining the successful blasting of the drawbell and undercut but requires a larger vertical separation between the Undercut and Extraction Levels to ensure there is sufficient rock pillar to allow the transmission of abutment stresses during cave establishment. Pre and Advance undercutting techniques utilise similar undercut ring geometries and involve “choked” or confined blasting, as a result these blasts need to be well executed to ensure that there are no pillars formed which can act as cave back span interrupters and impact the cave initiation. The latest versions of the Advance undercut implementation design are now becoming larger and requiring additional material to be removed from the Undercut Level, a level not set up for material transport, which has many functional impacts during the cave establishment phase of the mine.

The productivity of the Extraction Level is determined by many factors, including:

- Layout design, including location of the tipping point(s),
- Tunnel size,
- Equipment selection,
- Tramming distance for the LHD,
- Roadway design for the LHD,
- Fragmentation size of the ore, and
- The number of Extractions Drives and drawpoints available

The draw strategy for caving initially focusses on ensuring the complete destabilization and caving of the targeted ore block and the management of the “airgap” between the caveback and the caved muckpile above the drawbells and undercut, this then changes to targeting the highest value material whilst deferring the ingress of waste material into the cave column. To achieve these objectives whilst maintaining the porosity in the cave column the draw strategies for the Extraction Level involve the regular extraction of material from all drawpoints. The productivity of the level is defined by the longest tramming length, from the drawpoint to the dumping point, and the performance criteria of the LHD units.

Near field ore flow is influenced by the integrated blasting geometry of the undercut and the drawbell. The preferential flow of the finer blasted fragments, from angles higher than the angle of repose, leads to void creation in locations other than directly above the drawpoint.

During the initial phases of the cave establishment the larger fragmentation associated with the early caving can impact the performance of the cave as it requires additional treatment

in the drawpoint, potentially even blocks up a drawpoint, or at the dumping point. The impact of the larger fragments can be mitigated by installing a crusher on the Extraction Level allowing for the tipping of larger rocks without congestion. Layouts which utilise orepasses either inside or outside the footprint can only accommodate smaller fragments as they will have a grizzly on the top to limit the size of rocks entering the pass to reduce the chance of the orepass hanging up. The decision as to which dumping arrangement is selected relates to the mines overall materials handling system and the ground conditions on and outside the footprint. Due to the size of the chamber required to accommodate a primary crusher they will generally have to be placed some 50 to 150m from the edge of the nearest drawpoint to ensure they are in stable ground, and this adds to the tramming distance required to be travelled by the loaders every trip. The smaller excavation for the orepasses located outside the footprint mean that they can be located closer, nominally 25 to 50m from the edge drawpoint and as they are outside the footprint can be larger in size, diameter and length. The orepasses located inside the footprint result in the shortest tramming distances for the loaders but are often the smallest in size as they are located inside the layout and require the excavation of additional development in the layout pillars to be installed, they are also usually only able to be installed after the abutment stresses have passed over their proposed location.

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.

As Extraction Level footprints are getting deeper and the operating environments are becoming more challenging with declining grades, increasing stress and heat so there is an immediate requirement to enhance the design, functionality and costs associated with

establishing and operating the levels.

2.8 What needs to change

To ensure the Block Cave method is a viable alternative for the challenging conditions (technical, financial and social), expected in the future there are a number of areas which need to change, including:

- Efficiency. The future footprints need to replace not only the existing BC footprints but the current large scale open pits, which are reaching their operating limits, to ensure the future supply of metal to the world markets. This requires the existing performance expectations to be raised and the footprints to become more efficient on a tonnes per square metre basis.
- Reliability. The future footprints need to ensure reliability of ore delivery from stable layouts which accommodate the variability of the rock masses, stress redistribution and changes in the fragmentation and flow characteristics over the life cycle of the Extraction Level.
- Cost Reduction. The future caving deposits are likely to be in more challenging conditions with declining grades, so to maintain the operating margins in the future the footprints need to be established and operated at reduced cost to the current ones.
- Time Improvements. The world demand for metals, particularly green metals, is increasing and the requirement to reduce the lead time to nameplate delivery of new deposits is paramount. The current timeline from initial study through development and cave establishment is in excess of 10 years, this needs to be reduced particularly in the cave establishment phase once the project has been committed too.
- Financial Returns. To ensure ongoing investment in the method there needs to be improvement in the financial proposition of future Block Cave mines. The current long lead times and significant upfront investment can make the decision to commit to a new Block Cave project challenging as they do not generally compare well on the traditional financial evaluation metrics including Net Present Value (NPV) and Internal Rate of Return (IRR).

With improvements in the timeline to nameplate capacity, increases in production rate with greater reliability of ore delivery and reduced establishment and operating costs the financial position of future caving projects will be enhanced and ensure the viability of the method to deliver the world's metal needs.

Chapter 3

3 Research Proposal

3.1 Research Proposal

3.1.1 Problem Statement

With the increasing depths and design challenges of the Extraction Levels for the current and future caving footprints the existing industry footprint designs are being pushed beyond their technical and operational limitations.

Over the last 50 years of operating the El Teniente and Offset Herringbone layouts the industry has identified a number of restrictions to be considered during the design of the proposed caving mine, including;

- Breaking large footprints into “macroblocks”, essentially Block Cave footprints, rather than utilising the Panel Caving method with a slow but constantly moving undercutting front that progresses at the same rate as the mature drawbells are completed,
- Targeting the higher-grade portion of the footprint as a “starter” footprint to improve the project economics and create a foundation for future lower value blocks,
- Increasing column heights, well beyond the past averages of 200m, that cannot be accommodated in a Panel Cave approach as they result in an almost stagnant cave front,
- Restricting the undercut front to less than 350m to ensure a reasonable undercut front movement rate to minimise stress build up during undercutting,
- Extraction Level stability is a higher priority than draw cone interaction due to the potential impacts of losing access to drawbells and Extraction Drives,
- Large infrastructure chambers need to be located outside or below the abutment zone, the area of increased stress created during the establishment and extraction of the ore block
- Capital investment in a caving mine is expensive with a long lead time to first production so establishing the Minimum Viable footprint which delivers the desired production rate without compromising/sterilising the rest of the deposit is the

preferred investment strategy,

- To spread the capital investment across the largest tonnage possible the height of draw columns has increased which leads to stability, fragmentation and recovery issues whilst putting larger portions of the deposit at risk if the cave doesn't perform as expected,
- LHD performance directly influences the productivity of the footprint and is restricted by the size of the Extraction Drives, drawpoint infrastructure and the tramming distance to the dumping point (crusher or ore pass).
- To improve the stability of the Extraction Level the drawpoint spacing is increased to improve the amount of in situ rock left in pillars, if this strategy doesn't achieve the required stability then the Extraction Drive sizes are reduced to further increase the in situ rock pillars,
- To offset any reduction in Extraction Drive size and the subsequent reduction in LHD capacity the tramming length of the LHD needs to be reduced to maintain the productivity targets, which leads to the installation of ore passes either close to the edge of the footprint or within it,
- Use of autonomous loaders which have a potential productivity reduction of up to 40%, as observed at some operations, compared to manual operation,
- The financials of the mine are highly influenced by the performance of the mine during the cave establishment period, increasing productivity in the early years without compromising safety is the goal

3.1.2 Aims & Objectives

The principal objective of this research is to reengineer the footprints associated with Block caving to maximise their safety, productivity and economics. The research will identify the key design components required for an Extraction Level and then propose design and system configurations to overcome the variability inherent in hard rock material properties and conditions in most, if not all, deposits. The focus will be on redesigning the physical layout and redefining the materials handling system on the Extraction Level. As part of the reengineering process an operational review in terms of the equipment, supporting systems, workforce skills and the overall operating environment required to make the new physical mine design and associated systems successful will also be undertaken.

The thesis will outline the research areas and functions required to support a transition from the existing El Teniente dominant layouts to a redesigned Extraction Level incorporating a 4-sided drawbell and a reconfigured materials extraction system. Economic and schedule

assessments will be undertaken at Concept Level (± 30% accuracy) to provide information on the impacts of change and to promote further discussion on the focus areas of the research.

3.2 Hypothesis and Research Question(s)

3.2.1 Hypothesis

A revolutionary Block Cave footprint utilising a 4-sided drawbell and a segregated on-level loading and hauling material movement system is not only safer but technically, operationally, and financially superior to the El Teniente layouts which currently dominate the industry. The incorporation of new and emerging technology to support the mining process will further enhance the outcomes of the new footprint design.

3.2.2 Research Question(s)

During the project the following focusing question, and sub questions, will be used to guide the redesign and operating strategies associated with a Block Caving footprint.

Acknowledging the complex interactions of technical, design, implementation, and operational aspects of a Block Caving footprint, how can the safety, stability, caveability, productivity, ore recovery and financials be improved by redesigning the layout and associated materials handling and management systems?

1. What needs to change, in the design and establishment of caving footprints, to enable a reduction of 30% in the time taken to achieve nameplate production, without compromising the long-term productivity of the footprint?
2. What are the key economic parameters that influence the economic performance of a Block Caving mine and how can they be revised to improve the economic returns?
3. Which technical areas have the largest influence on the successful extraction of the target ore block and how can they be enabled in the mine design and execution strategies?
4. What design and operational strategies are available to minimize, and ideally eliminate, major hazards from a Block Caving footprint?
5. What design, caveability, operational and management risks are reduced using the new footprint and what new risks are introduced?

3.2.3 Research Design

The research project will be broken into four areas, Technical, Equipment and Technology, Management systems and Real-world condition testing.

The stages of the Thesis will involve:

- Technical:
    - Developing a design matrix incorporating the key design criteria driving the Extraction Level design,
    - Undertaking stability assessments on the proposed footprint using industry leading tools such as Flac3D to validate the stability improvements during the life cycle of the footprint, specifically during cave establishment and operation, and
    - Undertaking flow analysis using industry endorsed products such as Beck Engineering's FS4 to validate the flow performance of the proposed layout. This includes the impacts of reducing by half the total number of drawpoints for any given footprint and increasing the size of the draw parcels from each drawpoint.
- Management systems
    - Develop Establishment and Operational logic for the new design to identify the technical and non-technical areas which require modification from what is currently done to maximise the value of the new layout,
- Equipment and Technology:
    - Assess the equipment and technology available and identify the gaps in what needs to be developed to support the establishment of the "optimal" Extraction Level for future environments,
    - Specifically investigate the loading and hauling technology available, including battery charging and payload capacity to refine the design of the drawpoint, loading and discharge areas.
- Real-world condition testing
    - The hypothesis will be tested using real world conditions as supplied by industry (Carrapateena Block Cave) and comparing the results of the new design, establishment, and operating strategies against the results of an industry study at a Concept level (±30% level of accuracy). The comparison areas will include schedule, capital and operating costs, productivity and total metal recovered from the footprint.

3.2.4 Sustainability Contribution

This research will lead to the sustainability of the mining industry through the efficient extraction of metal from underground with a reduced impact on the environment as the footprint is easier to electrify than the current options. The new mining approaches considered in the research will lead to a new generation of mining employees with remote operating opportunities to support a flexible workforce strategy.

3.2.5 Resources and Skills

Commercial resources were required to run the flow analysis software as the proposed software, FS4, is commercially controlled. FS4 has been developed by Beck Engineering over a number of years and is based on real world data analysis and calibration from a number of large-scale caving operations.

Industry data was used to test the PhD hypothesis. This data included rock mass properties, stress conditions and mine operating guidelines. OZ Minerals, now part of BHP, and Freeport McMoRan provided data from their caving operations and projects.

All data was managed using the UQ RDM platform including the HDR Enhancement project. This ensured compliance with UQ HDR milestones and governance.

Whilst existing technology can be utilised in the new concept, there are opportunities to use emerging technology to further enhance the potential of the new concept, such as:

- Electric, battery powered, hauling units,
- Haag loader or similar for loading at the drawpoint, this would increase the productivity from the drawpoints beyond that outlined in this paper, though existing units would require modification to allow larger fragment sizes to be handled,
- Mechanical cutting to improve the development rates and limit the damage to the pillars,
- Draw zone knowledge from existing caves via smart markers to confirm the impacts of variable fragmentation and draw sequences on the cave movement zones, and
- Equipment tracking and collision avoidance technology to manage the interaction of haulage units and other activities (including personnel) on the Extraction Level.

Additional industry personnel to assist with the development of the research include:

- Anthony Allman, Antcia Consulting, to assist with the computer design work associated with the mine design and scheduling scope. Anthony has over 20 years industry experience working for various mining companies and consultants. He has

been the lead design engineer on a number of caving studies in the last 10 years including Ridgeway Deeps and Ernest Henry.

- Adrian Pratt, Independent Consultant, to assist with the Operational Readiness, Infrastructure and equipment associated scopes. Adrian has over 30 years' industry experience and is a leading author on numerous infrastructure associated technical papers. He has a wide range of experience covering studies, construction, operational readiness and post project reviews.

Advisors for the research were:

- The late Prof. Gideon Chitombo was the principal advisor for this research and was an internationally recognised leader in the Underground Mass Mining field.
- Dr. Rodney Hocking currently employed with Resolve Mining as Mining Consulting Manager.
- Mr Pasqualino Manca currently working for Newmont as Study Director Caving and is a former Co-Chairman of CaveMining 2040 Horizon 1 research project being run through Mining3.
- Mr Peter Choules, Emeritus Consultant with AECOM engineering.
- Prof. Peter Knights who took over as my principal advisor with the passing of Prof. Chitombo and is recognised as leader in equipment reliability and system safety design.

3.2.6 Barriers to Success

As the redesigned Extraction Level and operational philosophy are a revolutionary shift from the existing industry standards there are several barriers to success, as outlined in Table 1.

Table 1: Barriers to success

Identified barrier	**Risk management approach**
The revised mine design, of a 4-sided drawbell, is so different to the designs (2-sided drawbells and SLC rings) assessed in previous research that much of the previous research has limited application and new flow theories are required to support the hypothesis.	Flex the cave flow assumptions and validate with physical models and flow marker data from caving operations. Engage with industry leading specialists and utilise flow tools based on physics rather than observation.
The amount of work required to consolidate all the research areas outlined in this thesis are identified to be excessive and unachievable in the timeline associated with a PhD.	Monitor the depth of analysis in individual areas of the PhD to ensure delivery within the acceptable timeline.
Real world data is not forthcoming to enable the testing of the hypothesis and it remains a purely academic research task.	Engage with industry representatives to trial and implement the new design and operating logic on a small scale, or in a dedicated section of a deposit.
The balance of trade-offs doesn't work technically or financially. Compromises are required which detract from the overall research objectives.	Critically evaluate the trade-offs at each decision point. Select options which enhance the overall objective rather than just the individual item.
Low grade/weak rock mass deposits remain unmineable despite advances in knowledge and mining related technology.	Identify the areas required to be solved to enable successful extraction in the future.
Existing industry technical leaders do not accept some of the updated flow and fragmentation-based assumptions and learnings despite agreed evaluation and modelling approaches being used.	Engaging with key industry professionals as formal and informal advisors to this thesis to take them on the journey and alleviate their concerns.
The industry is not yet willing to embrace a revolution in Extraction Level design and operating philosophy.	Due to the large investment, time and capital, required in establishing an Extraction Level there will be a natural resistance to change. Continued design reviews and small-scale trials to confirm the key design and operational logic of the new design will be required prior to the industry embracing the new approach.

3.2.7 Contributions to Knowledge

The currently available literature is focused on the narrow technical areas of flow,

fragmentation, stability and caveability with limited research pulling these areas together. This research is expected to fill the gaps in the academic literature by providing an integrated approach to the research relating to the design, establishment and operation of a Block Caving footprint. It is not expected to redefine the individual academic areas but rather draw from them and utilise the latest knowledge to revise the state of the art in Block Cave mining.

The contributions to knowledge identified from this research include:

- Improved productivity from the caving footprint from a reconfiguration of the material handling logic and associated equipment, including the opportunity for electrification and automation of key machinery,
- Higher overall ore recovery from the targeted ore block due to the technical, operational and economic improvements of the footprint design, including a more stable layout which accommodates the variable fragmentation and chaotic flow within the draw columns and enhanced draw strategies to increase mass flow, leading to the ability to successfully extract higher (>1000m) draw columns,
- Improved safety on the caving Extraction Levels with the reduction of personnel from the active production area through the redefinition of tasks following an Operational Readiness review. Reducing exposure to seismic events and material (dry and wet) rushes from drawpoints, and
- Reduced capital investment per tonne of ore and reduced operating costs per tonne of ore, by greater than 20 and 35% respectively.

The main knowledge gap exposed in this research is the flow behaviour of material in the cave column. The existing research is based on single access drawpoints, SLC and bin flow theory, and has been expanded to dual sided drawbells using observation, including flow markers, scale models and computer programs based on both. Whilst a substantial effort has been placed into fundamental research regarding flow behaviour (Pierce 2010), (Power 2004), these are often contradicted by the observations at the drawpoint (Brunton, Lett et al. 2016) and (Paredes 2022). The challenge is then being able to predict the flow behaviour from a different shaped drawbell in the future. A new generation of flow modelling software is being developed which is based on physics and this will be used for flow simulation estimates as it is not restricted to the current layouts and is malleable to new geometries and draw approaches. To validate the new code, tests were conducted for it to recreate the results of the sand model scale tests used as the basis of the existing codes which it was able to replicate thus confirming its validity.

The area which needs to be investigated is in relation to the interaction of four-sided draw. The old sand models only look at draw from crosscuts next to each other, in a Sub Level Cave (SLC) style or neighbouring draw points along an Extraction Drive, not in a drawbell situation where the draw is from opposite ends of the drawbell. The understanding of how depth of draw impacts the influence area of the draw and therefore the interaction of movement zones is crucial to understanding and defining the drawbell geometry. Industry flow modelling software utilises the sand and physical model results to influence the draw and recovery software logic. This logic may not have been correctly applied due to the two-sided drawbell geometry. The depth of draw and the shape of the drawbell brow will influence the shape of the extraction zone and have a large bearing on the movement zone interactions.

Correctly identifying a drawbell and material movement system, which encompasses and accommodates the various fragmentation sizes through the draw column over the life of the drawpoint, is crucial to the success and functionality of the Extraction Level footprint. To this end mobile equipment is the preferred extraction and materials handling system for the Extraction Levels as it can accommodate larger fragment sizes than fixed infrastructure such as conveyor belts. The proposed new design and materials handling system will include services and the ability for the battery-operated equipment to recharge whilst travelling on the designated routes, through conductive charging or an overhead pentagraph style. There will be identified haulage paths and fixed loading locations. The loading units being investigated are the existing LHD style, including diesel, battery and tethered electric, or the continuous loading style unit such as a Haag loader. To improve the productivity of the haulage system it has been decided to separate the loading and hauling functions with the hauling function to be done using existing diesel or battery power 50t to 65t haul trucks which can be operated manually or autonomously (Figure 38).



Figure 38: Sandvik 55t Battery Haul Truck

Scheduling options to be considered in the new design and establishment approach include minimising development firings and therefore the need to clear the active firing zone and reducing exposure times of personnel to the high stress abutment zone once caving has commenced. Consideration also needs to be given to the ventilation flow quantity and direction requirements and the movement of people and materials on the Undercut and Extraction Levels. A breakdown of all tasks to establish the drawbells and undercutting needs to be considered to identify opportunities for improvements in scheduling and cost expenditures.

Drive dimensions are important for the equipment selection and for ongoing/long term stability of the levels. Stability analysis will be conducted to generate a ballpark appreciation of the relative pillar strength for the new design compared to the existing El Teniente layout.

New technology to be considered and implemented as part of the improved system includes, but not limited to, battery operated mobile equipment, traffic management and collision avoidance systems as part of a bespoke autonomous mobile network, wireless detonators, software for optimization of schedule and draw control, remote operations rooms located on the surface or at a companies preferred office location. It is important to remember that no matter how much autonomous equipment and systems are included, there will be a requirement for manual intervention on the Extraction Levels and with the systems themselves for maintenance and the control of production interruptions and unforeseen

events, thus the operating environment needs to be suitable for personnel to work.

Chapter 4

4 Concept Advancement

4.1 New Extraction Level Proposal

The new layout proposed as part of this research is a revolutionary concept utilising a 4-sided drawbell to improve pillar stability without compromising ore recovery called the Cube layout. Loading material is possible from all 4 drawpoints in each drawbell at the same time if required. Due to the geometry of the layout, all of the pillars between the drawbells are the same. As such the Major and Minor pillar descriptions are associated with the location of the pillar, i.e. above the Extraction Drive or above the Link Drive, rather than their size. The pillar geometry allows for the Extraction Drives to be mined in the preferred direction for material transportation to the fixed infrastructure rather than being dictated by the principal stress direction. The Cube design also improves the time to establish the cave and the productivity per square metre of the footprint through the redefinition of the mobile haulage options on the Extraction Level.

The proposed layout is comprised of a series of perpendicular Extraction, Link and Drawpoint drives on 25m centerline spacing (Figure 39), all drives are 5m wide and the Link and Drawpoint 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. The base of the drawbell is 12m across both intersecting drawpoint drives and 15m high. The Undercut Level is located 50m (floor to floor) above the Extraction Level and has parallel drives on 50m centrelines, with perpendicular slot drives on 50m 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.

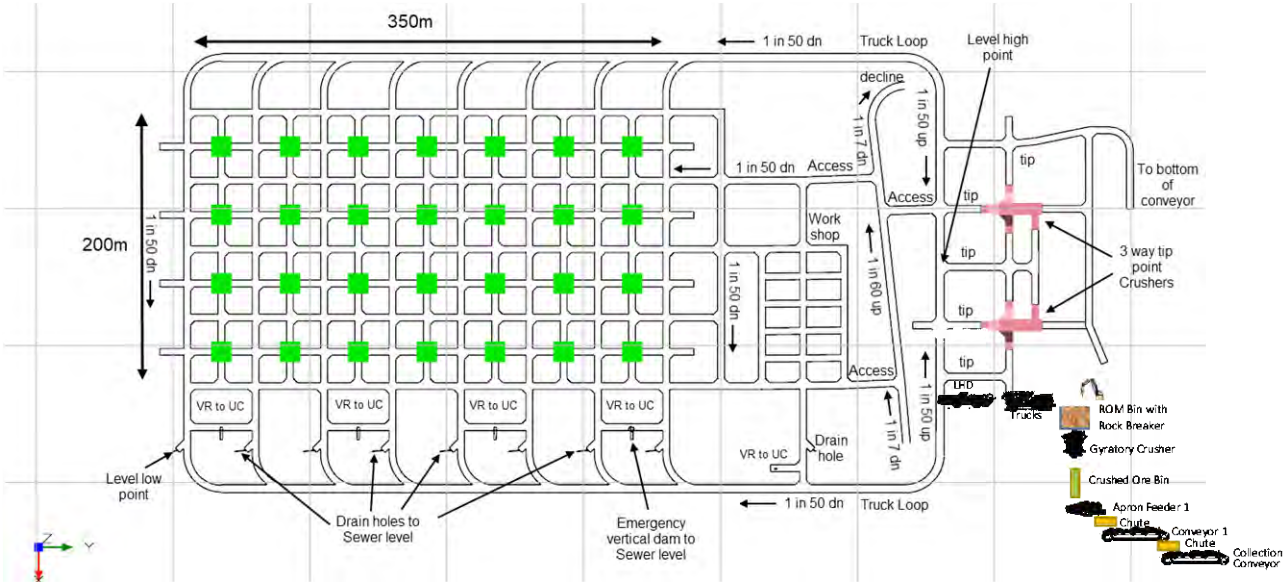


Figure 39: Plan view of the Cube Extraction Level and Materials Handling System

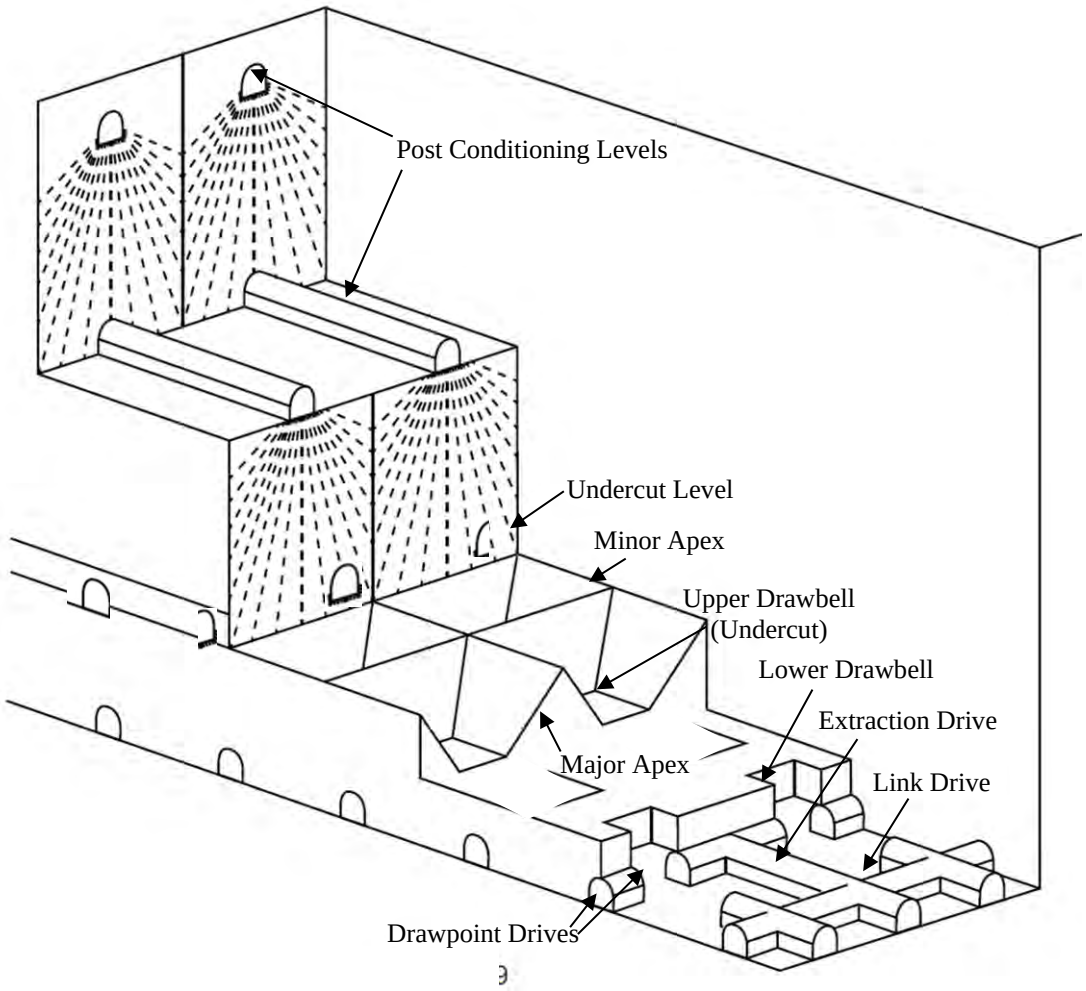


Figure 40: 3Dimensional Overview of Cube design

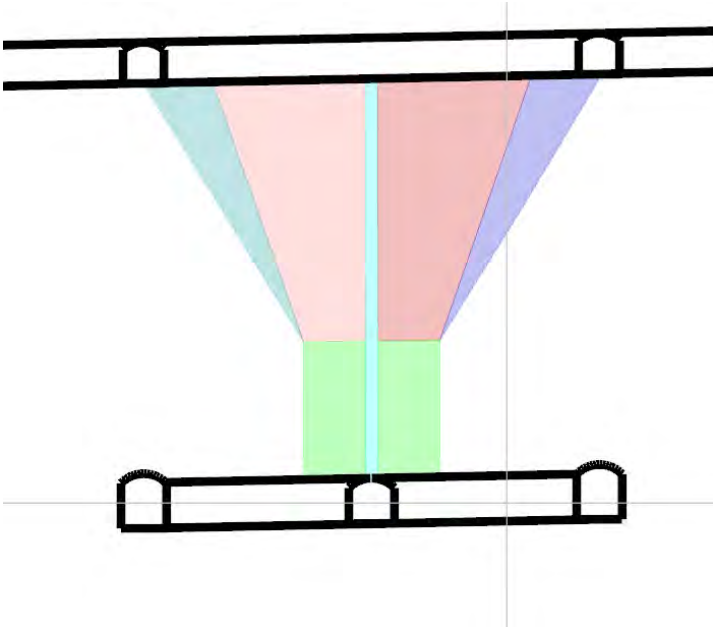


Figure 41: Drawbell and Undercut Firing sequence

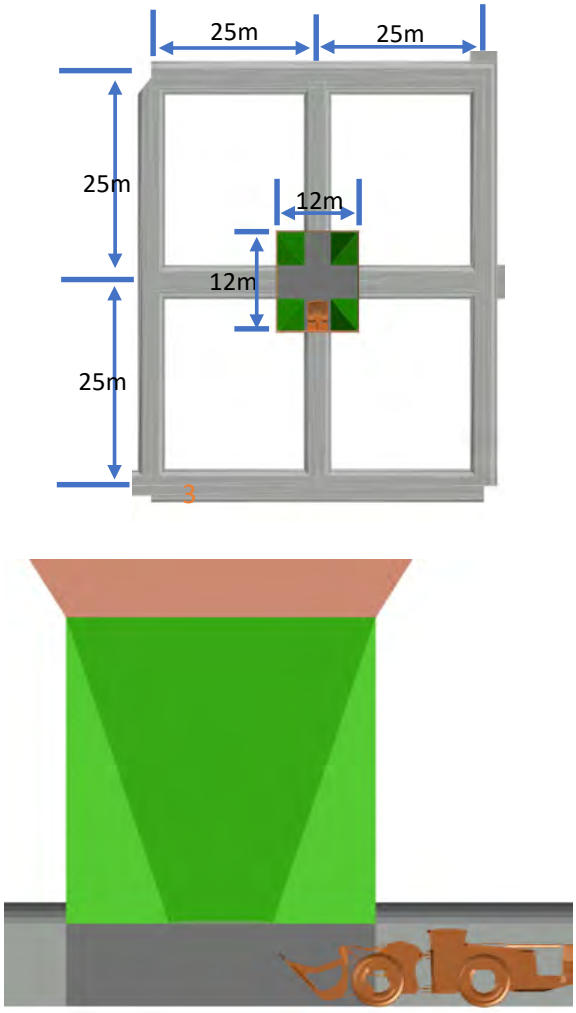


Figure 42: Cube geometry dimensions

Whilst the intent of the Extraction Level is clear in terms of safe and efficient ore removal there are many factors to consider when laying out the level.

4.1.1 Key Design Criteria

The design of a Block Cave Extraction Level involves the evaluation and trade-off of numerous interlinked criteria (Arancibia, Carrasco et al. 2008), including but not limited to,

- Stability,
- Ore Recovery,
- Dilution Management,
- Productivity, and
- Materials Handling System (MHS) restrictions

Further to these the author has added,

- Ventilation flow direction,
- Water drainage, production and major ingress water flows,
- Production equipment primary travel routes, and
- Secondary equipment and personnel movement

The stability of the Extraction Level has been prioritized as without a stable Extraction Level the safety of the workforce and the productivity of the mine is compromised. The proposed layout has an improved excavation ratio compared to the existing El Teniente Block Caving layouts. The stability has been further increased by making the pillars square and reducing the amount of wall stripping to maximise the pillar core dimensions. The significantly increased vertical separation of the Extraction Level and the Undercut Level also increases the amount of in situ rock remaining to transfer the stress changes associated with cave establishment and the operation. These pillar modifications enable the extraction of much larger tonnages from the drawpoints than is currently achieved.

Ore recovery is a function of the shape and spacing of the drawbells and drawpoints. Through the reshaping of the drawbell to ensure that there are no ledges or impediments stopping the flow of all material in the cave column from reaching a drawpoint, the extraction effectiveness of the footprint is increased. The spacing of the drawbells is influenced by the interaction of the draw columns expected from the caved material.

The materials handling system (MHS) restrictions have been alleviated by dislocating the dumping point location from the drawpoint. This has been accomplished by designing the

level to have haul units, trucks or individual haulers, transit through the Extraction Level to be loaded. This has the added benefit of reducing the loader tramming requirements. Due to the larger pillars associated with the new layout it is possible to have larger than existing drives without compromising the stability of the Extraction Level. The larger drives allow for the larger trucks to enter the Extraction Level drives as opposed to the existing Block Cave designs which require the development on the Extraction Level to be reduced to improve stability and therefore require smaller and smaller equipment. With the existing layouts the reduction in equipment sizing results in a desire to reduce the tramming length of the LHD to maintain the desired production rates from the footprint. The only design lever available to reduce the tramming length is to locate the dump point utilised by the loaders closer to the drawpoints, this can result in a dump point just off the footprint or located within it. The loader dump point is also the beginning of the MHS. The location of the dump point will also influence the size of rock fragments which can be discharged successfully. If the dump point is at the crusher, then the fragment size is determined by the crusher configuration, though if it is at the top of an ore pass then the diameter of the ore pass will influence the fragment size (ore pass design theory would assert that a grizzly with openings one third the dimension of the ore pass be used to ensure that there are no hang ups in the ore pass, this though results in the openings in the grizzly restricting the flow of far smaller material as a function of the grizzly design used, the dumping velocity of the loader and the way particles flow and lock up when discharged from a loader bucket). By introducing ore passes into the MHS upstream of the crusher results in the rock fragment size that reaches the crusher being significantly smaller than the designed capacity and also creates a bottleneck in the system as the effective size of an oversized rock fragment entering the MHS is considerably reduced requiring additional rockbreaking capability at the dump point.

The traditional definition of oversize material in a caving operation being $2m^3$ is based on the size of an LHD bucket in the 1970's which were capable of holding between 4 to $5m^3$. This definition is no longer valid with the larger equipment available but also highlights that as the equipment and fixed components involved in moving material in the cave mine change, so must the definition of oversize. The author proposes that oversize be redefined as "the maximum fragment size which can pass through the ore flow system, from drawpoint to crusher, without needing to be reduced." Thus, the size of an oversize fragment will vary if the mine uses ore passes with grizzlies, direct tipping to the crusher and even then, it will be based on the size acceptable to the selected crusher.

Maximising the productivity of the Extraction Level needs to be balanced with recovering

the maximum value or amount of the targeted ore block through draw control and dilution management. Traditional draw strategies target an even draw down of the cave material to defer the ingress of dilution from above the ore block, this leads to the production rate of the Extraction Level being limited by the productivity of the drawpoint(s) furthest from the dump point.

4.1.2 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. Where possible, the ultimate drawbell should align with its surrounding drawbells to ensure there are no flat spots or intrusions between the drawbells which will lead to flat spots and pinch-points thereby interrupting the near and far -field flow of caved ore.

Often during the design of the Extraction Level and selection of the undercutting sequence, this key design component is compromised for reasons including, but not limited to, ease of development, undercut establishment and pillar design to assist with level stability. The two dominant layouts in use at present, El Teniente and Offset Herringbone, have an inherent flaw in their design as the drawpoint itself is established oblique to the orientation of the undercut which leads to compromised flow within the ultimate drawbell (Figure 43). In some of the newer caving mines established at depth, this issue is further amplified by increasing the spacing between the undercut drives and locating them directly above the drawbell, this leads to a shorter central firing of the drawbell but a much longer brow firing which is oblique to the pre-established undercut and can also result in a near vertical wall immediately adjacent to the drawpoint (Figure 44), thus limiting the flow into the drawpoint. Figure 45 shows the combined impact of the drawbell geometry and brow location on the near field flow of the existing El Teniente drawbells and the ultimately restricted effective flow area of the drawbell.

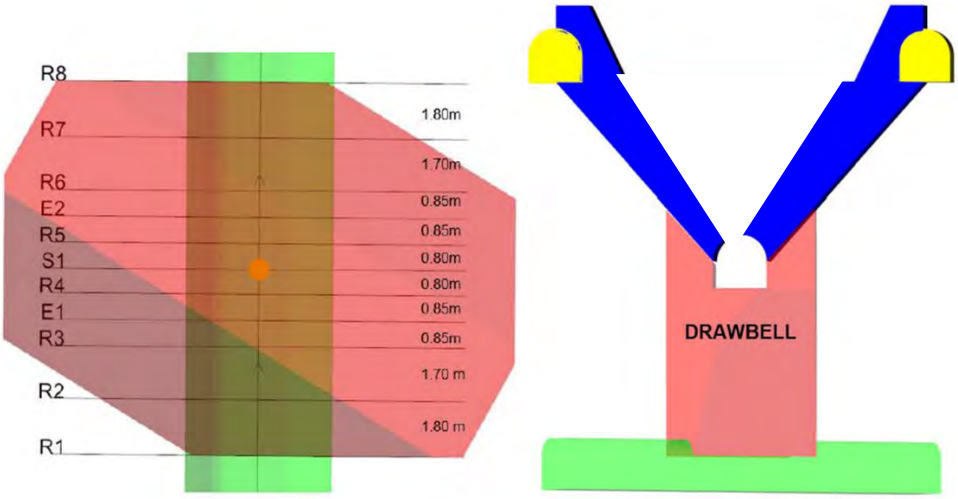


Figure 43: Drawbell and Big W Undercut Plan and Section View

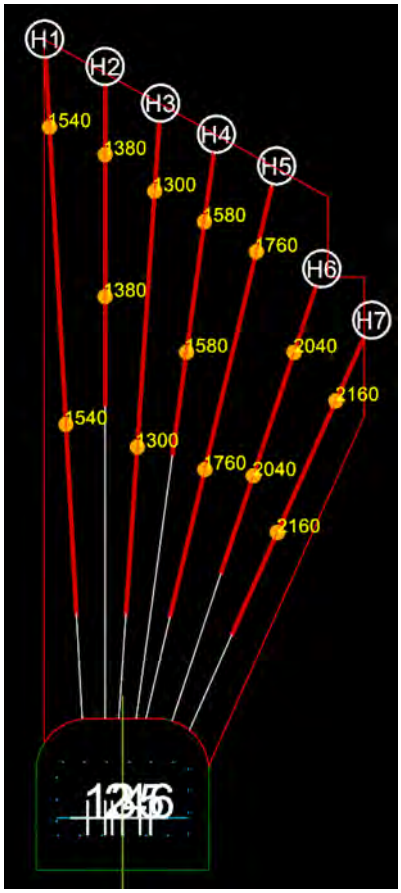
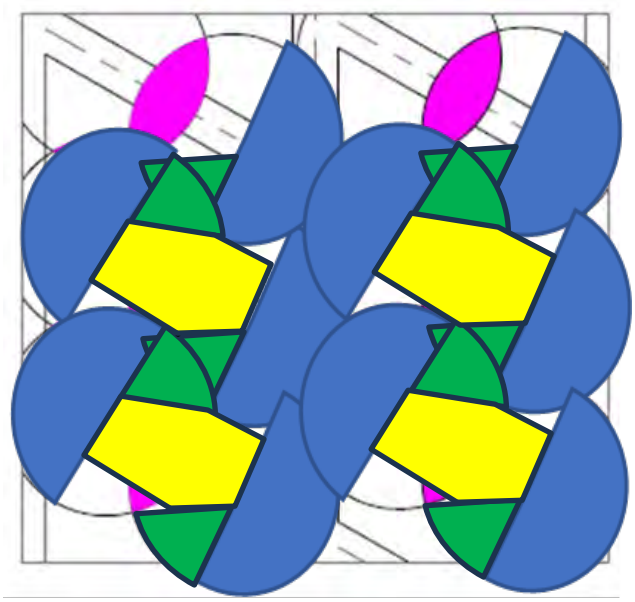


Figure 44: Drill pattern for the Drawbell brow



Blue – influence of Drawpoint brow
Green – Influence of drawbell shape
Pink – overlap of idealised draw cone
Yellow – effective "flow" area of drawbell

Figure 45: Existing El Teniente Drawbell and the influence of drawpoint brow and drawpoint geometry on idealised flow

The Cube layout created as part of this research fully integrates the drawbell and the undercut shapes to form an ultimate drawbell which is 50m wide in both directions at the top and seamlessly aligns with adjacent drawbells to ensure that all cave material will be directed to one of the drawpoints on the Extraction Level (Figure 40). The design also accommodates changes in fragmentation sizing over the life of the cave. 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 larger, this additional volume within the drawbell is gained in parallel with 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 each load and minimizes the opportunities for flow interruptions through pinch-points. The integrated design (Figure 41) 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 degree 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.

The general establishment sequence of activities to develop the Extraction Level and associated Infrastructure is shown in Figure 46, noting it is the sequence of events and doesn't necessarily require the full completion of one task prior to commencing the next.

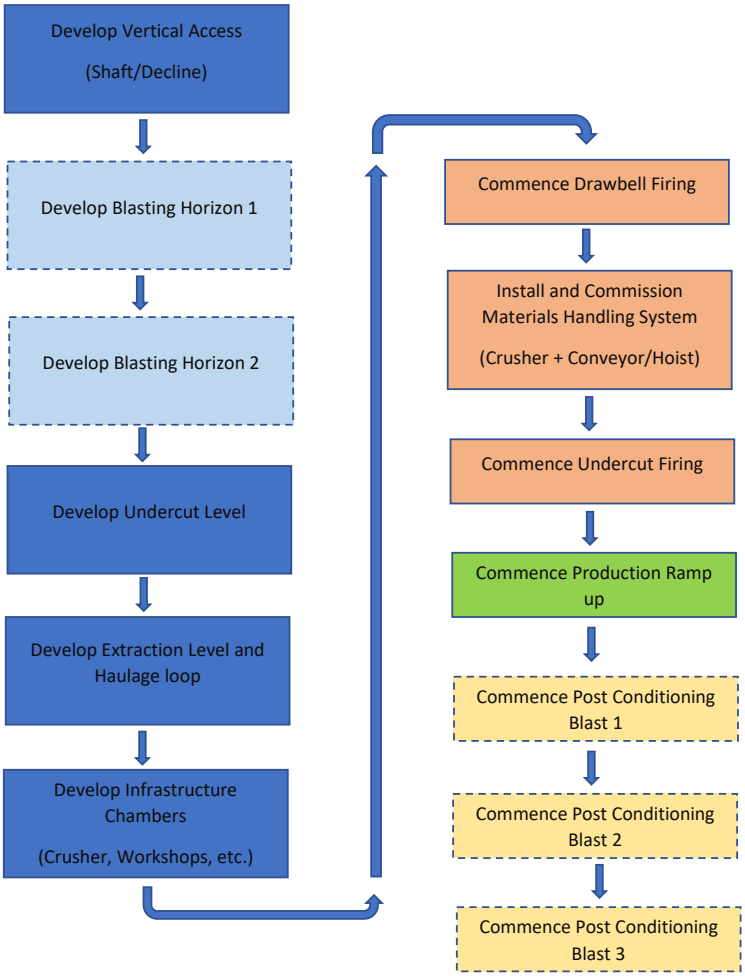


Figure 46: Cube Layout Establishment Sequence

Chapter 5

5 Extraction Level Stability

5.1 Stability Assessment of Proposed Layout

One of the industry standard modelling packages, Abaqus utilised 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 as it was the largest 'contemporary' footprint design that was assessed to maximise stability.

Freeport uses the same Beck Engineering model for footprint stability assessments. It has been calibrated against mine observations at Freeport (Beck, Hudson et al. 2016) to evaluate the failure criteria of Extraction Level pillars.

The more simplistic approach by Bewick at Freeport uses the Beck Engineering model forecasts from the global model as boundary conditions to drive smaller scale sub-models for ground support assessments. These methods rely on mine-scale, cave-coupled non-linear models to properly capture the evolution of stress and strains to reliably simulate stress paths and how strain (and damage) evolves over a life of mine. Itasca does the same for Cadia, with occasional modelling also conducted by Beck Engineering every couple of years as a comparison.

The purpose of the stability modelling was to assess the difference in footprint performance at a macro scale, rather than for ground support design.

5.1.1 Stability Modelling Workflow

The stability model establishment and assessment workflow was as follows

- Create sub-models with the different designs, 30m x 24m El Teniente and 50m x 50m Cube, to match the selected locations of the mine scale model footprint,
- Impose a Discrete Fracture Network (DFN) into each of the sub-models,
- Adjust the global mine scale model, from Freeport's DMLZ mine, to host the sub-models of the two drawbell layouts and run global simulations,

- Sequence the sub-models according to the mine scale model sequence,
- Extract mine scale deformation patterns at the boundary locations of the sub-models,
- Run the sub-models with different material properties and load histories taken directly from the global mine scale model, and
- Evaluate the cave loads and drive closure for each of the runs, limiting the evaluation to the centre region of the sub-models to limit edge effects

5.1.2 Model Inputs

To build the stability models a number of inputs were required.

Sub-model Location

A common location was selected for the sub-models within the Freeport DMLZ footprint, as shown in Figure 47. The DMLZ Extraction Level is located at ~1,350m and is below the exhausted DOZ mining block. The location was selected to allow an easy placement of the sub-model on the footprint and to avoid boundary effects from the outer regions of the footprint.

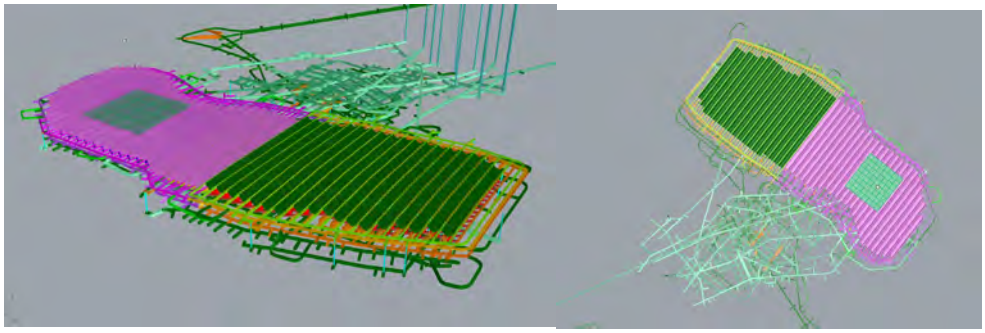


Figure 47: Sub-model location within the mine scale model

Footprint Geometry

The model design for the 30m x 24m El Teniente layout consists of 35 (5 x 7) drawbell ring cells and the 50m x 50m Cube layout consists of 16 (4 x 4) drawbell ring cells. The designs cover similar areas which allowed the sub-models to use the same location within the global model.

The drawbell ring cell layouts are shown in Figure 48. Figure 49 shows the sub-model designs.

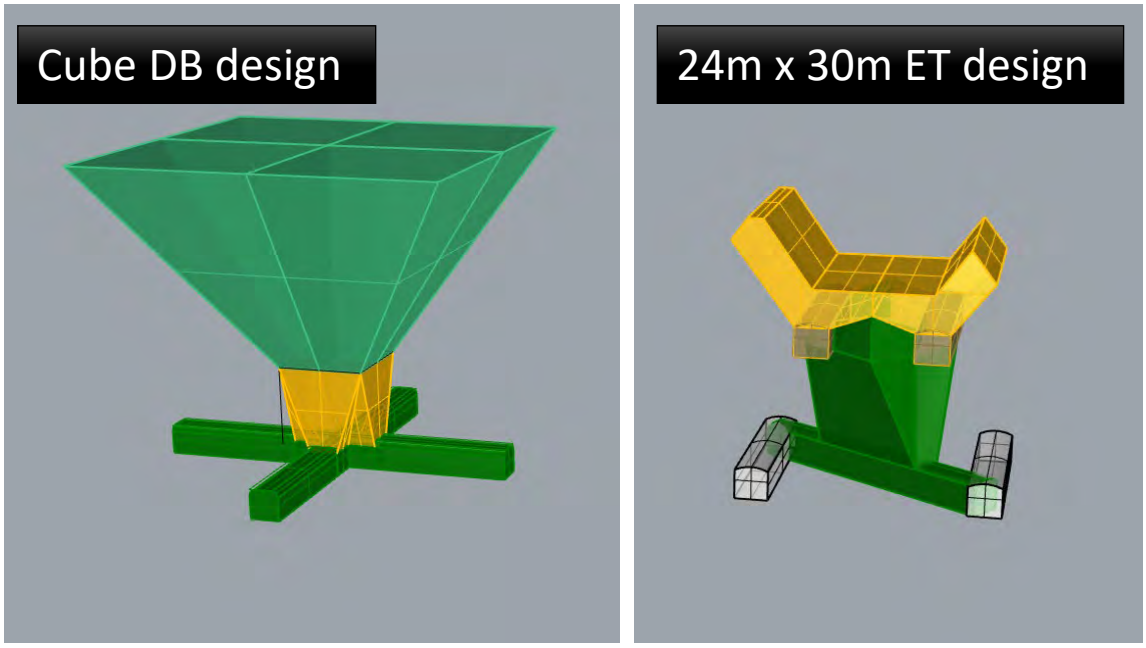


Figure 48: Drawbell ring cells for Cube and El Teniente layouts

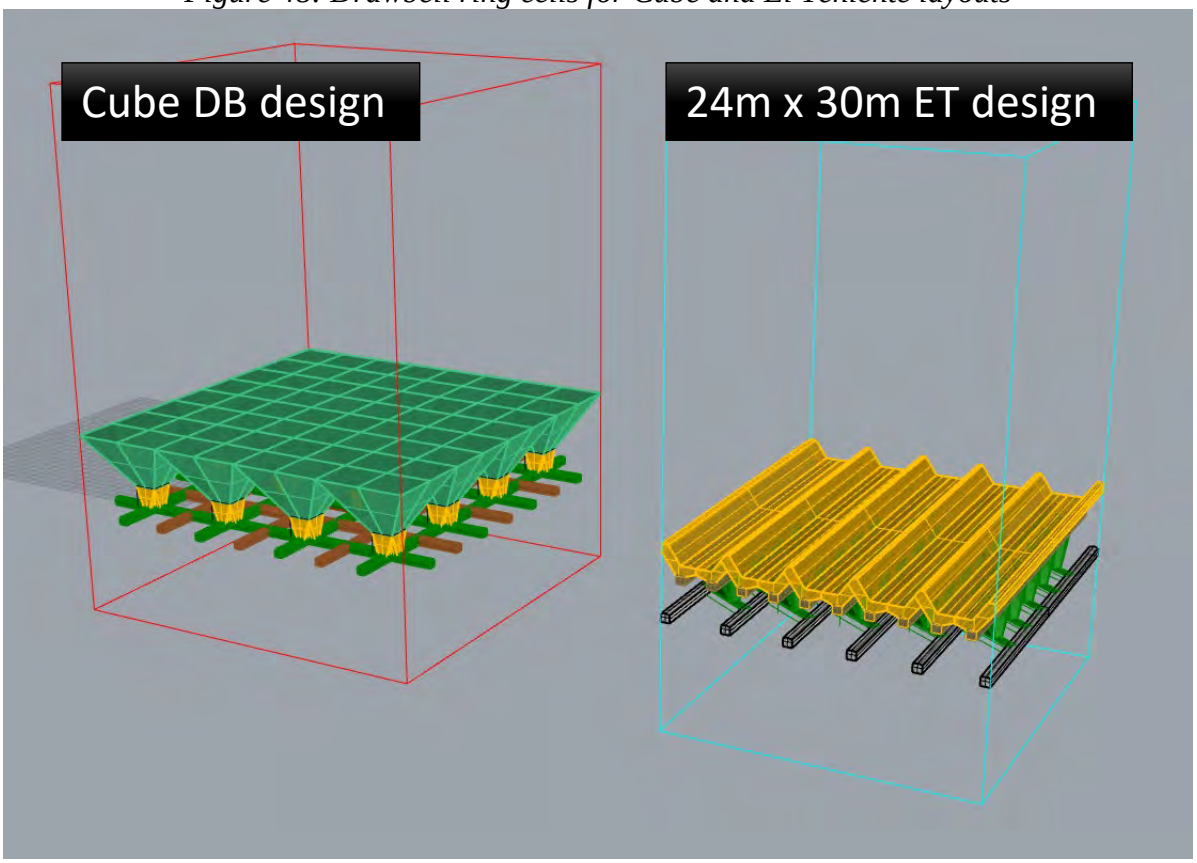


Figure 49: Sub-model designs for the Cube and El Teniente layouts

Discrete Fracture Network

For consistency both sub-models used the same, explicitly built Discrete Fracture Network (DFN) as shown in Figure 50. This was to remove any variability around rock type in the modelling. The different orientation of the Extraction Drives and the drawbells in the two designs relative to the DFN geometry led to varying effects in pillar damage and drive

deformation.

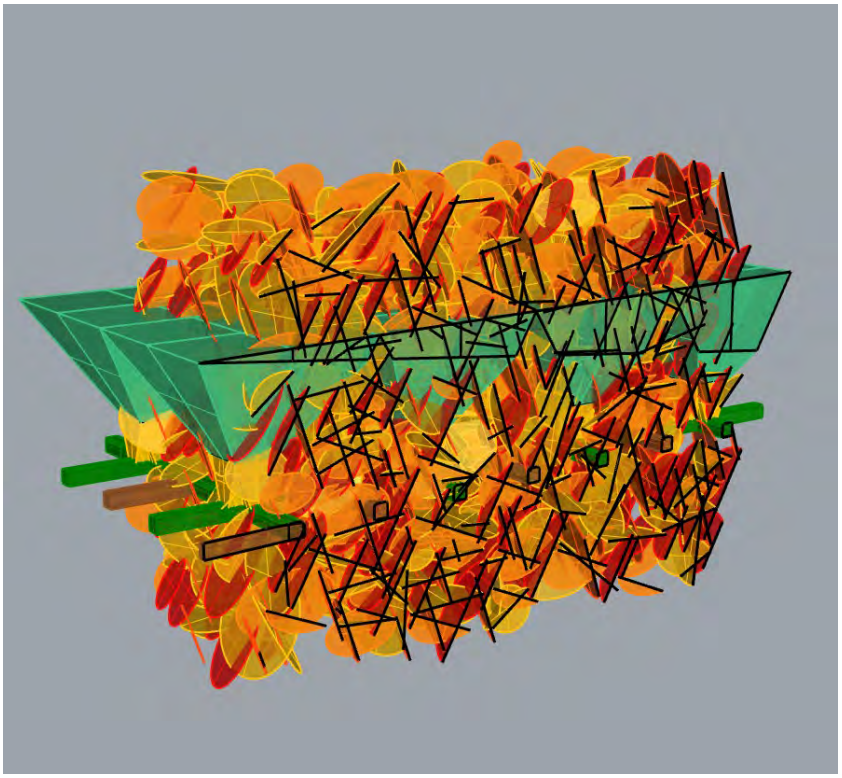


Figure 50: Discrete Fracture Network (DFN) for Cube Drawbell model

Material Properties

Two rock mass types were used in the models, Diorite, which is a stronger rock and Endoskarn, which is a moderate strength rock. The material property inputs for Diorite are shown in Figure 51 and for Endoskarn in Figure 52. Though for simplicity the sub-models were assumed to host only a single rock mass type. The rock mass properties were taken from calibrated material property data sets determined during the simulations of the global mine scale models at Freeport.

General Properties

Type	Computator V13 PLR
ρ [kg/m³]	2700.00
UCS_i [MPa]	120.00
GSI	60.00
n_{aniso}	1.00
s_{aniso}	1.00

LR2 Parameters

	PEAK	TRANS	RES
ε_{plast} [%]	0.00	1.95	3.41
E [GPa]	25.08	25.08	25.08
ν	0.27	0.27	0.27
s	4.38e-03	4.38e-03	1.91e-03
m_b	1.99	1.99	1.39
a	0.50	0.50	0.50
e	0.60	0.60	0.60
d	0.30	0.30	0.11

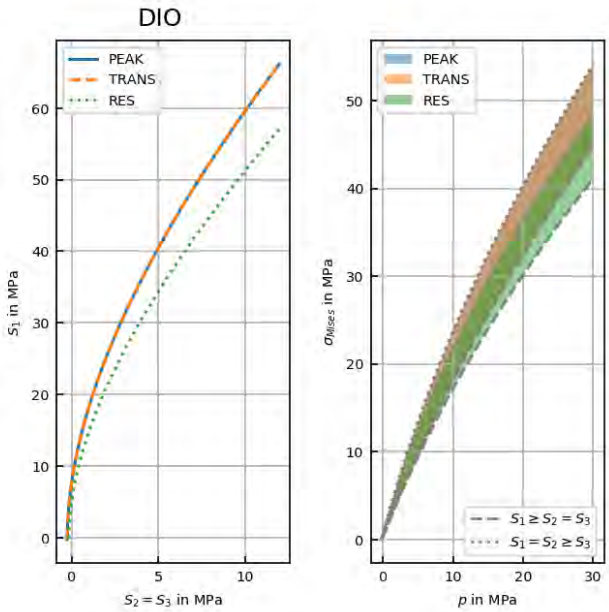


Figure 51: Diorite Rock mass material properties

General Properties

Type	Computator V13 PLR
ρ [kg/m³]	2700.00
UCS_i [MPa]	100.00
GSI	40.00
n_{aniso}	1.00
s_{aniso}	1.00

LR2 Parameters

	PEAK	TRANS	RES
ε_{plast} [%]	0.00	2.20	3.84
E [GPa]	20.90	20.90	20.90
ν	0.26	0.26	0.26
s	1.70e-03	1.70e-03	1.26e-03
m_b	1.09	1.09	1.09
a	0.50	0.50	0.50
e	0.60	0.60	0.60
d	0.25	0.25	0.09

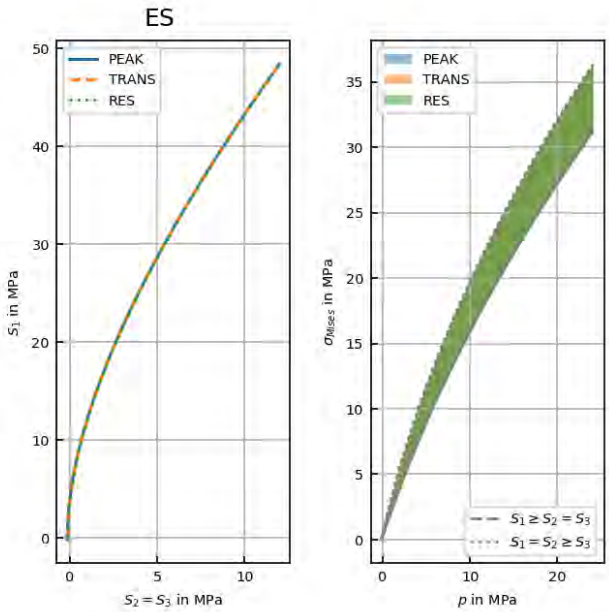


Figure 52: Endoskarn Rock mass material properties

Sequence

Both sub-models used the mine establishment sequence derived from the original sequence in the global model (Figure 53). The time span from initial blasting to full production is similar in both models as no cave establishment or operational scheduling improvements for the Cube design were included for comparison purposes.

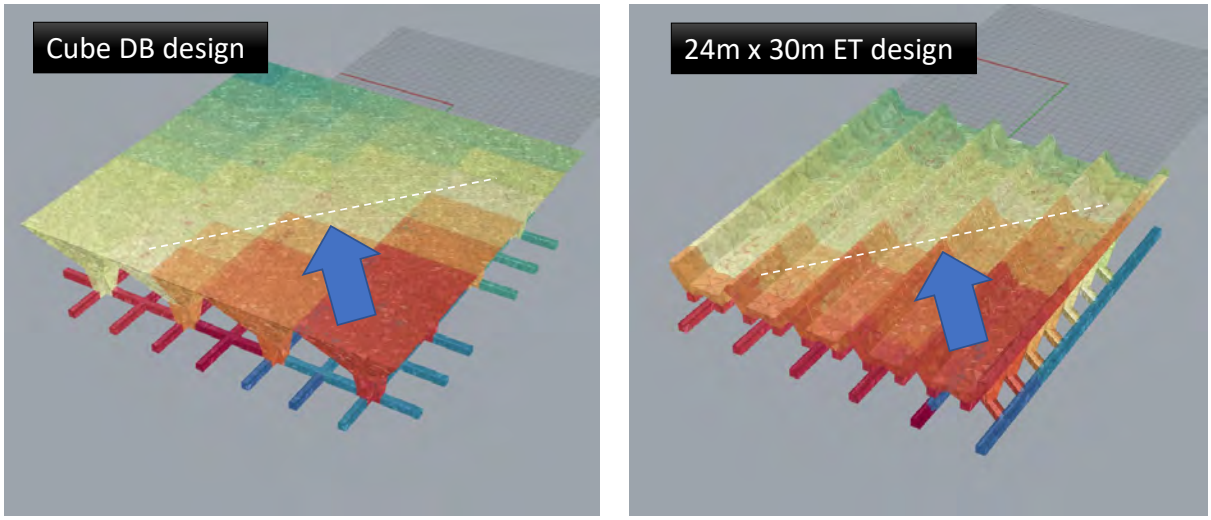


Figure 53: Sub-model sequences for the Cube and El Teniente layouts

Global Model

To ensure realistic load paths for the sub-models the global mine scale block cave model for Freeport was modified to provide the external load conditions (Figure 54). The mine scale model was run separately for each of the different designs and rock mass properties.

The original global model used for the simulation used an almost identical design to the El Teniente 30m x 24m sub-model design. As such the integration of the sequence and the alignment of the drive connectivity was more seamless than for the Cube design. Despite this, the drawpoint performance and the pillar performance in the centre of the sub-model is not affected in either option.

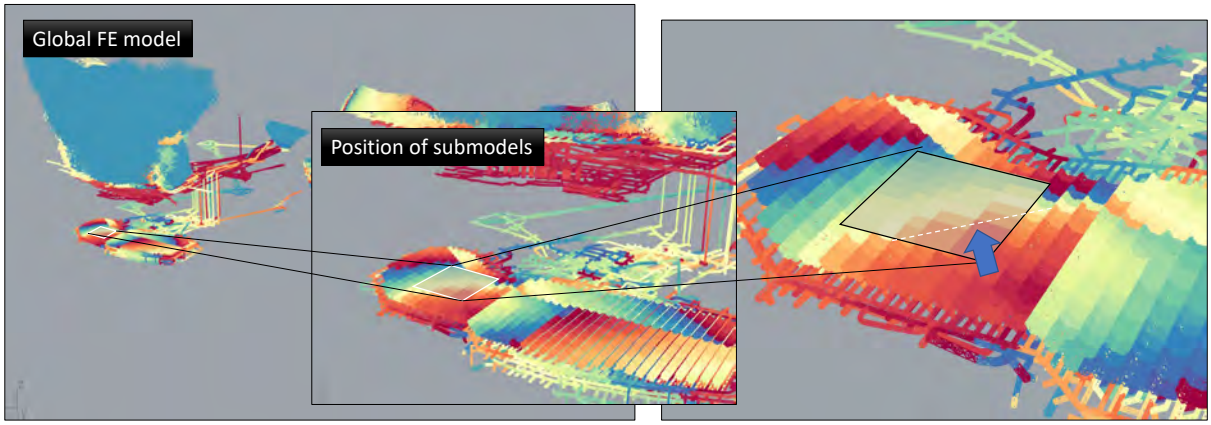


Figure 54: Location of the Sub-models within the Global Mine Scale model

5.1.3 Measurement Logic

All data was evaluated for the centre drawbell of the sub-model only (Figure 55) to limit any boundary effects. The results of a sub-model run were used to extract drive closure and

cave loads over the extraction sequence. These two quantities are used to create drive closure over cave load diagrams, Figure 56.

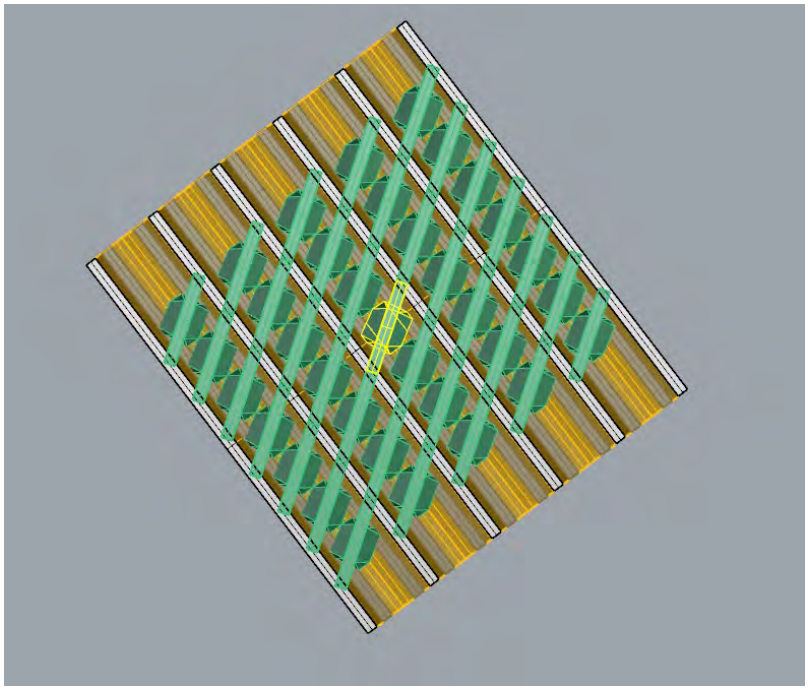


Figure 55: Central drawbell used for data collection (El Teniente layout)

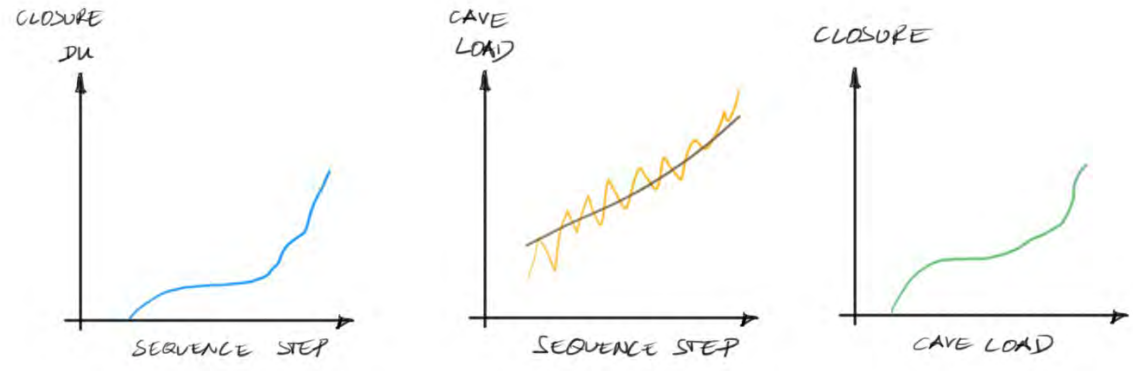


Figure 56: Derivation steps for Drive closure over Cave load diagrams

Drive Closure

Drive closure was measured at adjacent points of the drive walls, back and floor close to the drawpoints. The points were 2m from the openings in both models, Figure 57 and Figure 58. Vertically aligned points provided vertical drive closure and the laterally aligned points provide the horizontal closure.

Closure which occurs during the development of the drive excavations has been removed from the closure charts as the effect cannot be measured in the field.

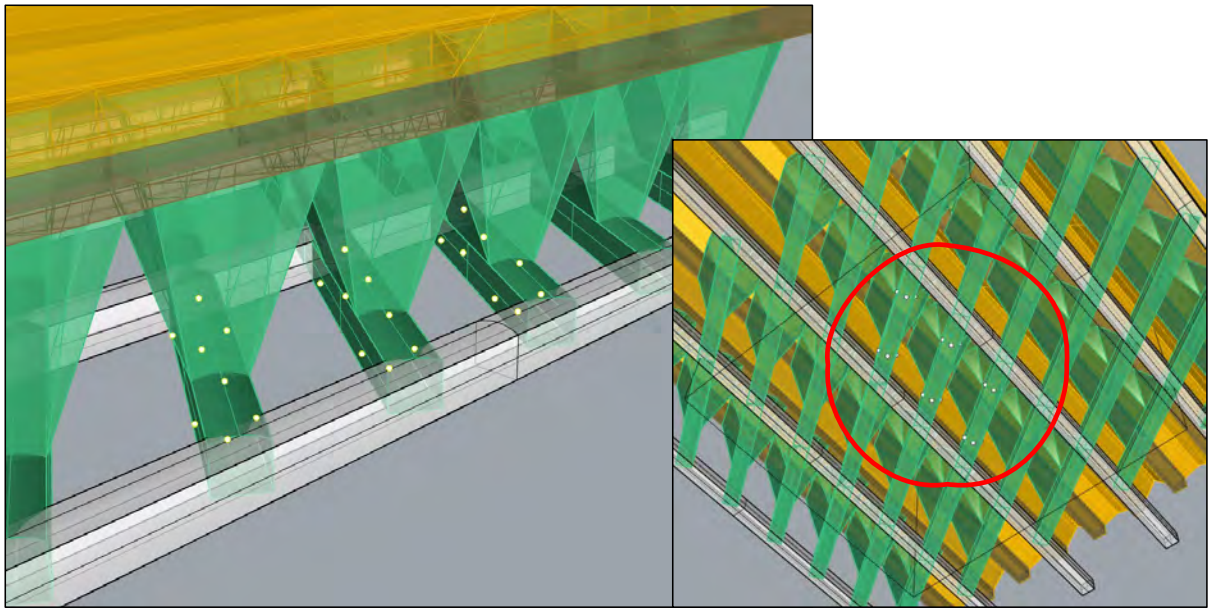


Figure 57: Closure measurement locations for the El Teniente design model

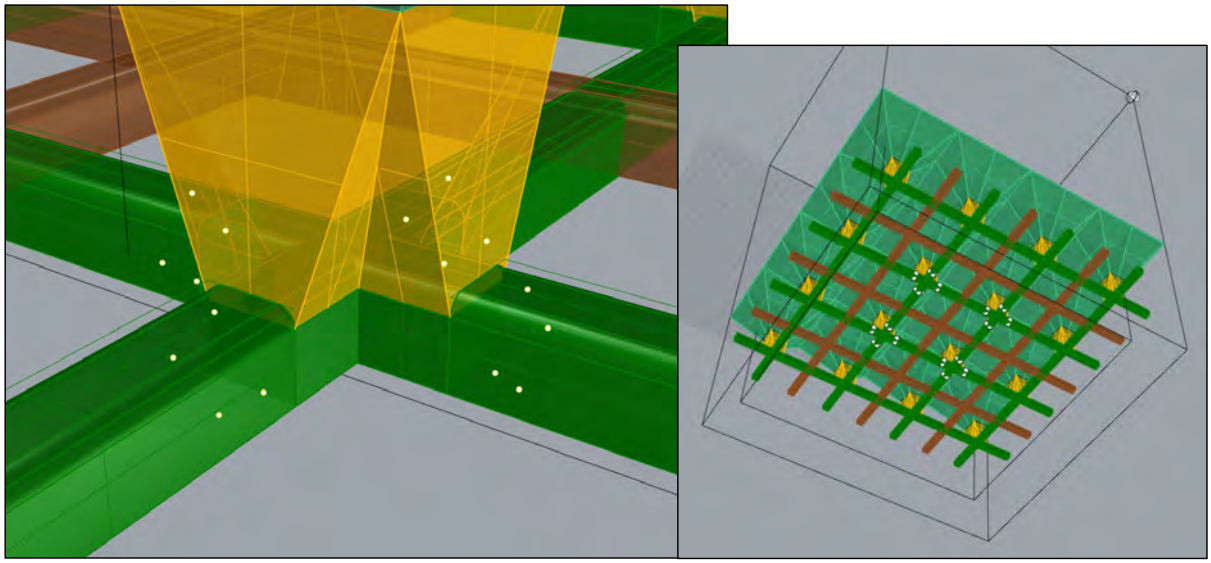


Figure 58: Closure measurement locations for the Cube design model

Pillar Stress

Pillar stress is measured in a point grid of 27 locations and averaged to provide a single representative value. Pillar loads do show some large spatial variability and time dependence due to the current production sequence. For simplicity it is assumed that there is a statically resting cave at the end of each production cycle, which are quarterly mining steps.

The rock above the footprint initially shows the current intact rock stress conditions which may have changed from the in-situ conditions due to nearby mining activity. The rock significantly destresses during the blasting of the undercut and then the cave loads increase

with cave initiation and growth. Sigma 1, the major principal stress, and Sigma 3, the vertical stress, magnitudes at Freeport are very similar as the major principal stress is vertical. Over time the loading from the broken cave muckpile contributes to the pillar loading. All models, both designs and rock type, show qualitatively similar evolutions of pillar loading.

At the end of mining the cave loads are artificially increased to test for stability effects (Figure 59). This is similar to a strength test in a laboratory where a rock sample is continuously loaded to test for potential failure.

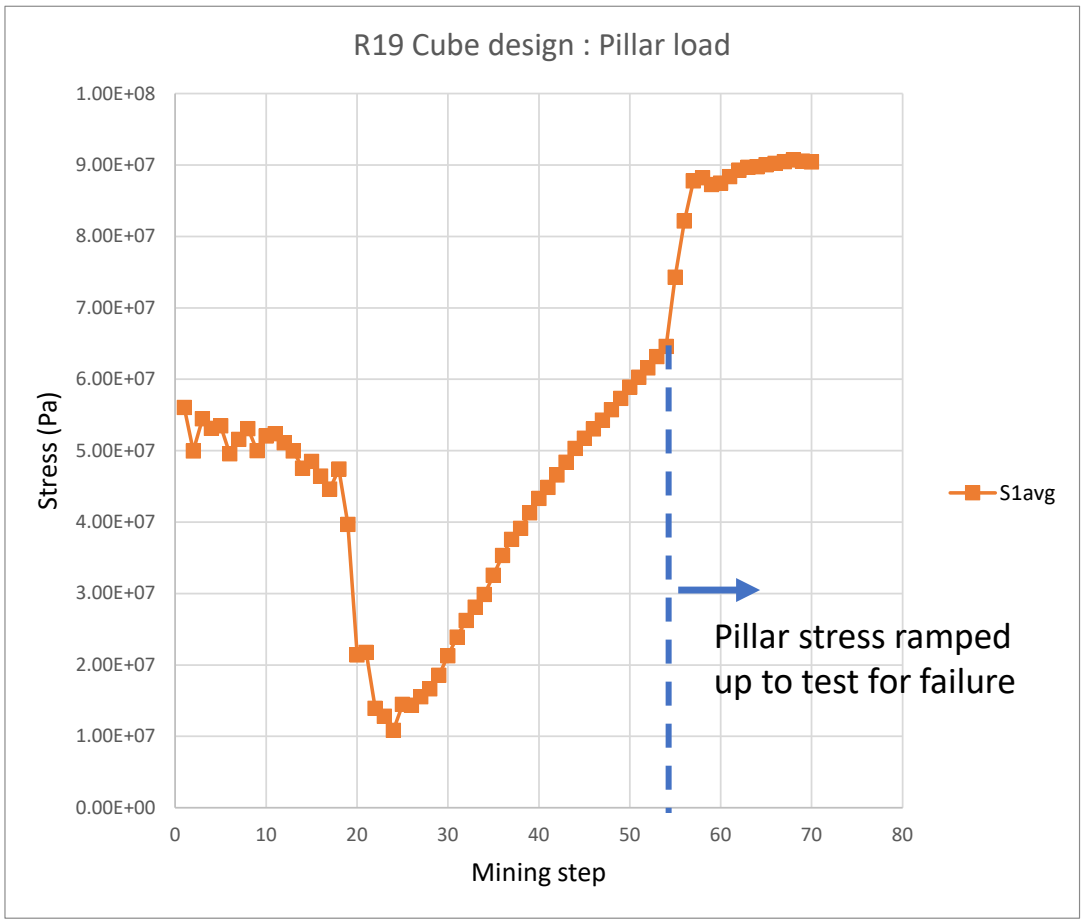


Figure 59: Example of Pillar loading over time in the sub-model for the Cube layout

Rockmass damage is a measure of plastic strain (Figure 60). Essentially rockmass damage in the model indicates deformation or movement. Beck Engineering uses damage in their stability assessments as it is a good indicator of deformation and can be readily identified underground (Figure 61). Damage and deformation do not necessarily mean instability and/or failure as these are subject to interpretation in a mine-scale model.

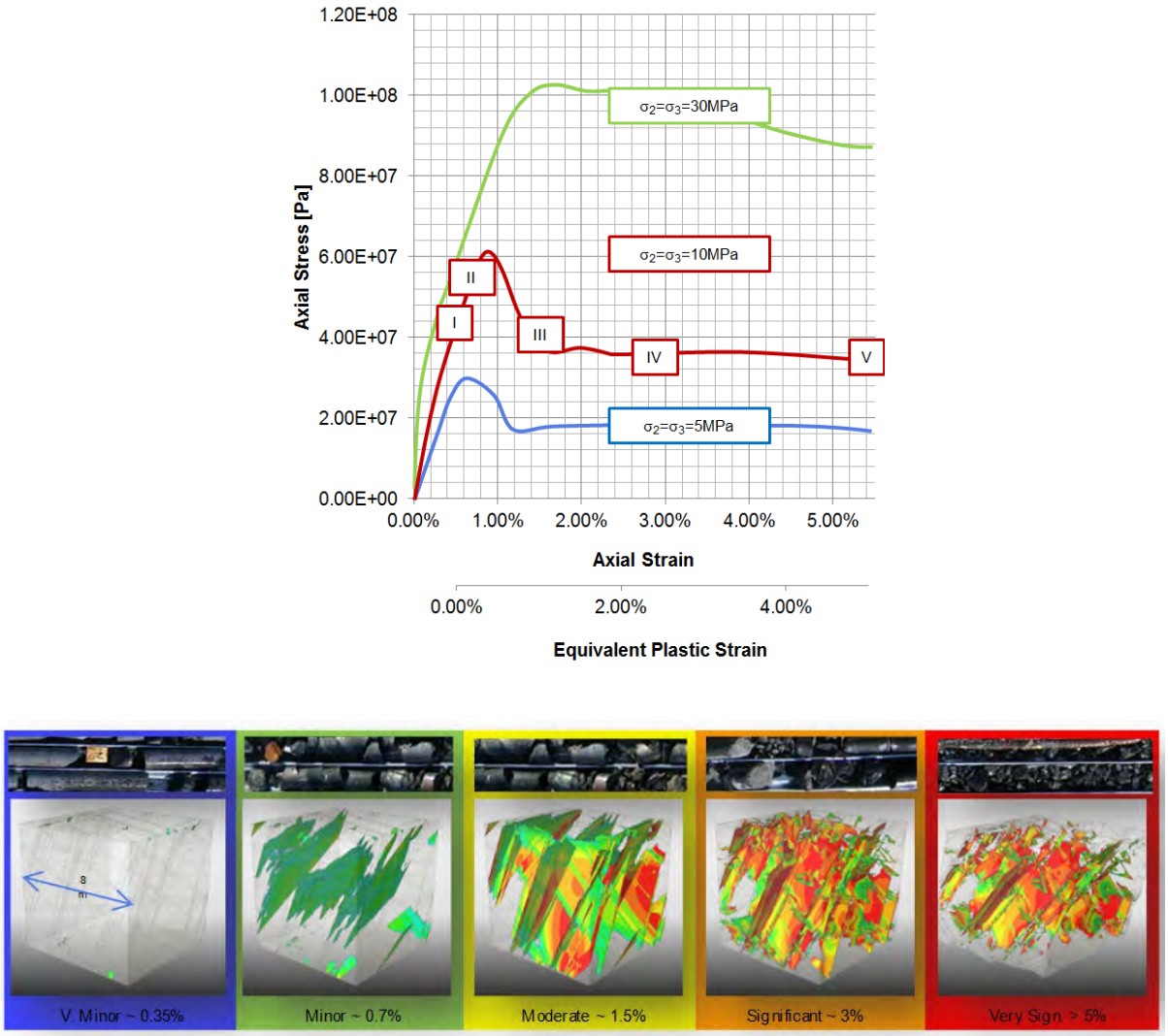


Figure 60: Logarithmic Rockmass damage scale

Damage Level	General Description	Example
S0	No visible damage	
S1	Minor damage	
S2	Moderate damage	
S3	Significant damage to excavations	
S4	Sever damage to excavations	
S5	Extreme damage to excavations Opening collapsed	

Figure 61: Practical Examples of damage classes (Sandy)

5.1.4 Key Design Considerations Identified from Modelling

As the Cube design utilises a Post undercut establishment sequence the Extraction Level is subject to significant stress change and potential rock mass damage during the mining of the large draw bells. The Extraction Level drives must be supported sufficiently to manage the anticipated levels of deformation.

In the event of establishing a footprint in extreme environments the mining of a horseshoe drive profile or dynamic ground support could be used to improve the drive stability.

5.1.5 Results of Footprint Stability comparisons between the Layouts

The Cube 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 design (Figure 62 and Figure 63). 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 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.

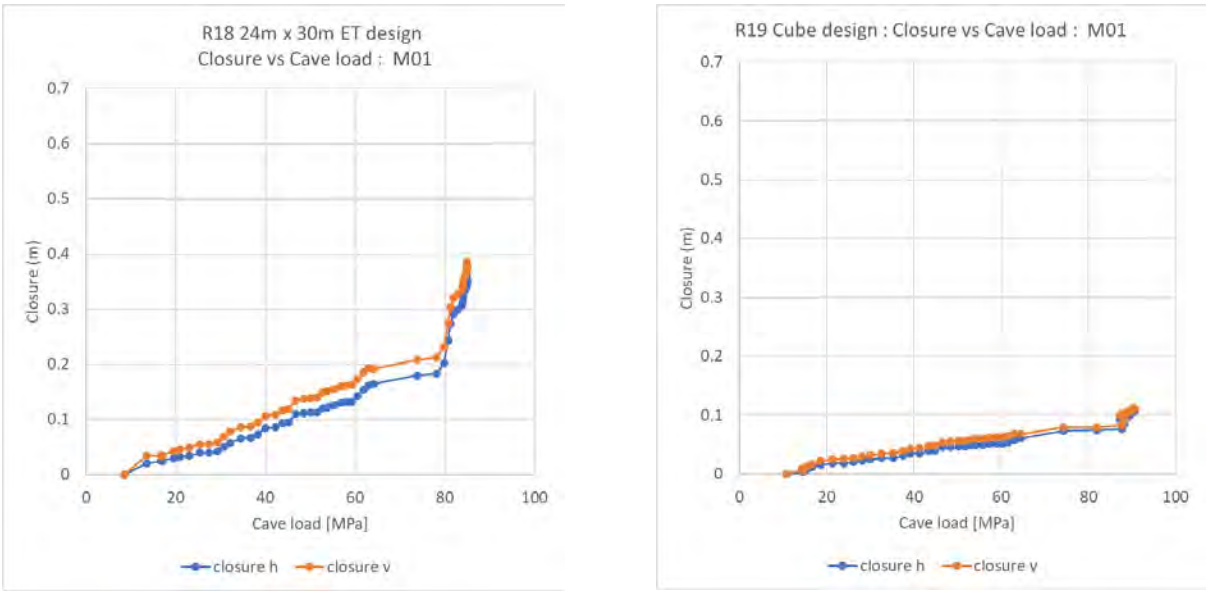


Figure 62: Drive closure comparison for M01 Cave Load

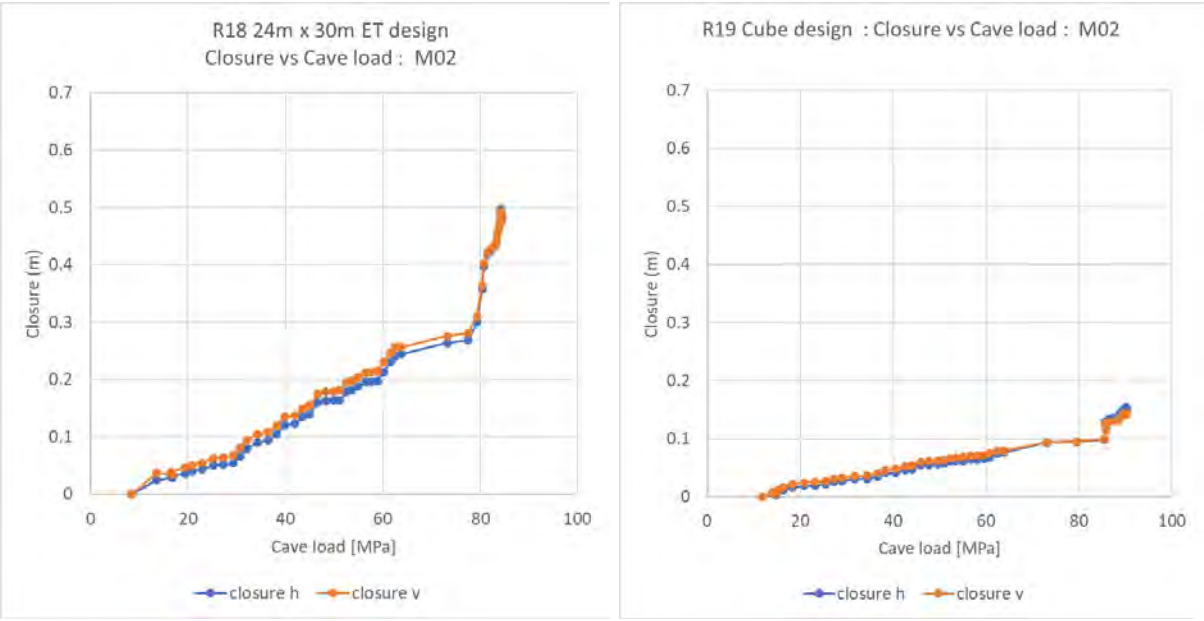


Figure 63: Drive closure comparison for M02 Cave Load

The presence of a DFN still induces locally significant damage at the openings of the drawpoints and along the crosscuts and Extraction Drives for both designs which means locally increased levels of ground support may be required when applied in the field.

Development in the Cube 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 64 and Figure 65).

In the El Teniente layout significant levels of rock mass damage extend through large portions of the pillars (Figure 64 and Figure 65). The onset of rock mass yielding begins to occur in pillar cores as the cave loads increase leading to large scale 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 compromised sections of the Extraction Level.

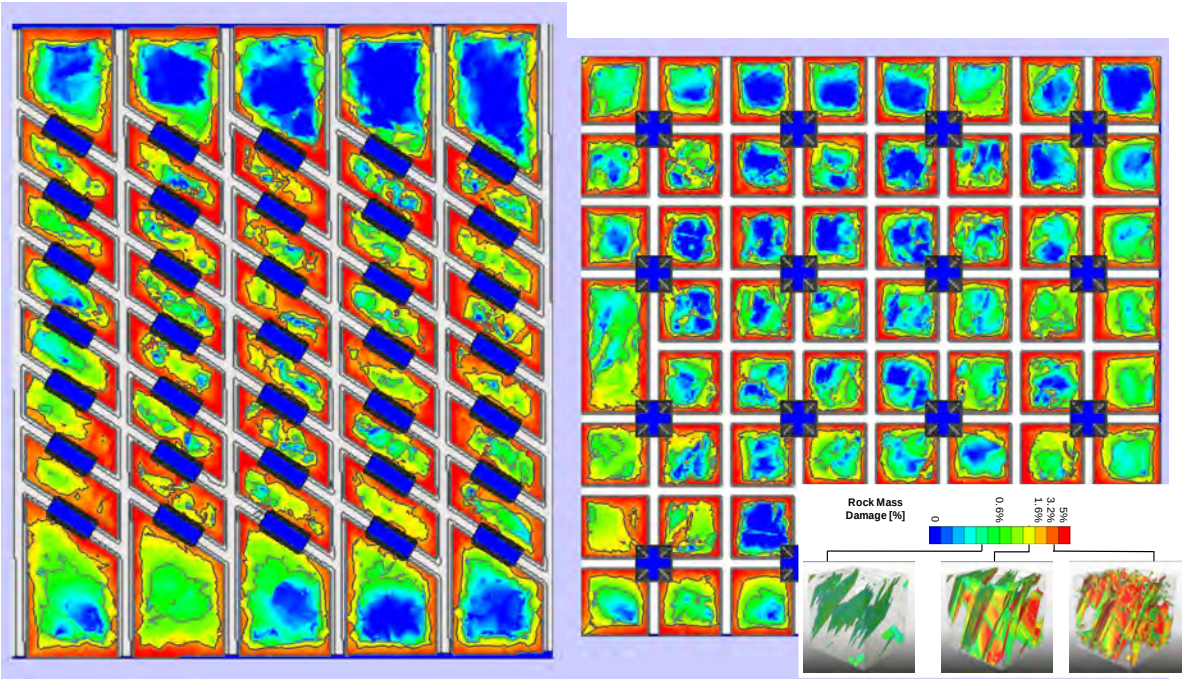


Figure 64: Comparison of Rock mass Damage for each Layout (Plan view)

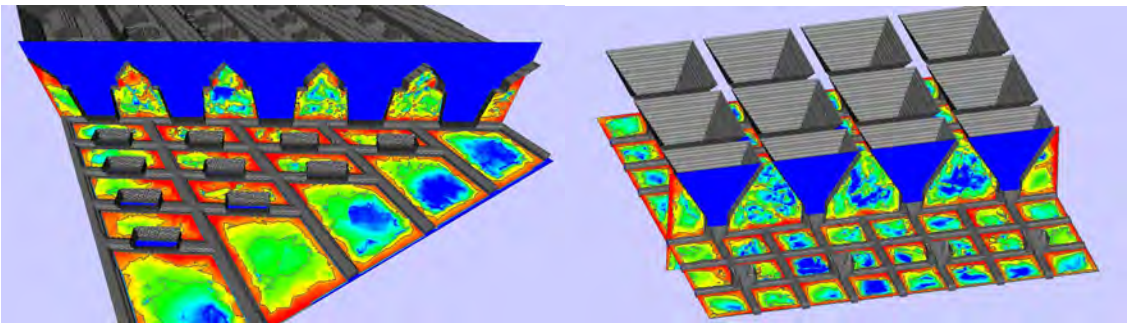


Figure 65: Comparison of Rock mass Damage for each Layout (Isometric)

Both layouts incur damage and drive closure effects induced by the blasting of the drawbells and the undercuts. The Cube design has slightly more damage due to the larger excavations however when the two footprint layouts are compared for drive closure performance only, the Cube design is superior (Figure 66 and Figure 67). The bigger pillars in the Cube layout increase the overall stability of the Extraction Level.

The charts showing the average movement in the drives are difficult to interpret. The initial charts showing the movement at multiple points are presented for each of the mining steps in the model, for horizontal and vertical movement, which includes the development of the drives. The combined charts are presented as an average of all of the movement points in either the vertical or horizontal plane but are shown relative to cave load, as such they are post the development phase where a reasonable amount of movement is initially identified. The deformation associated with the development phase is removed from the convergence charts as this is movement that the mine tunnel does not really see as this material and

movement occurs during the blasting process and is rehabilitated with scaling the backs and walls and the installation of surface ground support. The key deformation of the tunnels only occurs after the application of the final ground support and the cave is established over the Extraction Level drives.

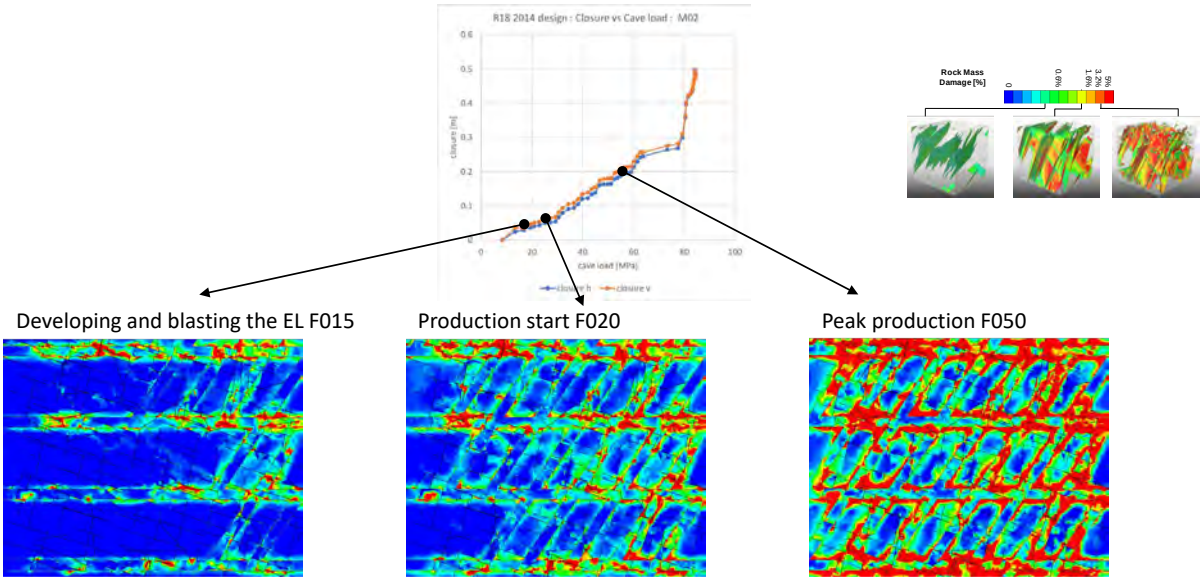


Figure 66: El Teniente drive deformation over time

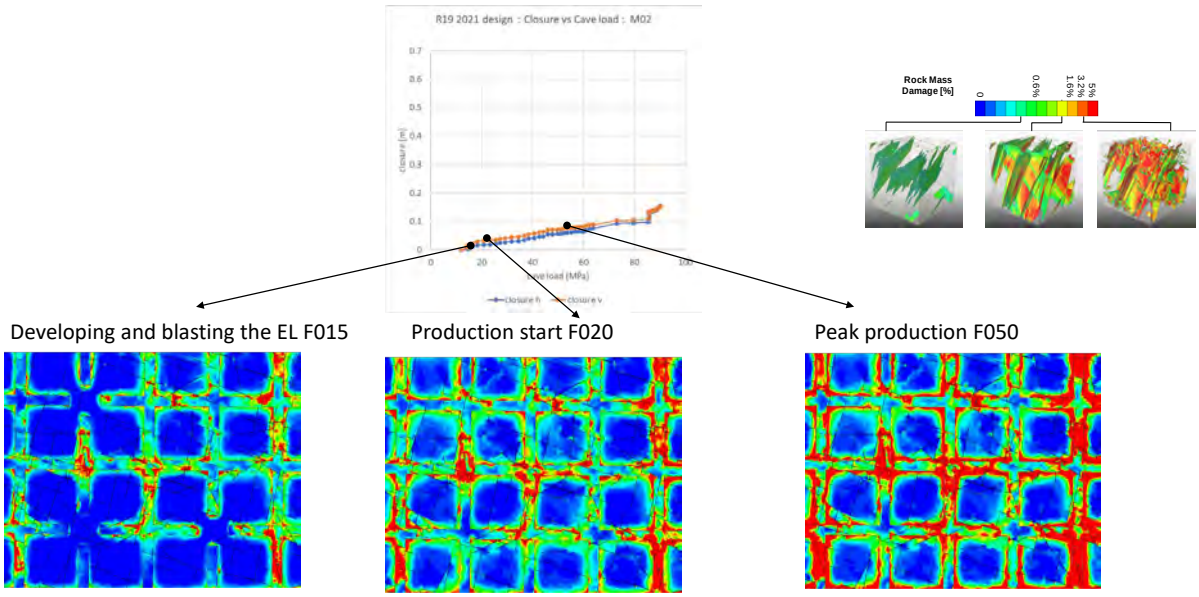


Figure 67: Cube drive deformation over time

As the Cube design utilises a Post Undercut design much of the Extraction Level is not "protected" in the way that an Advance Undercut shields the majority of Extraction Level development. As such the pillars of the Cube layout will be subject to large abutment stresses as the cave is established.

Similar to the El Teniente layout the main vulnerability of the Cube design is the 4-way intersections and the potential for deformation and damage of the drives during

development in extreme operating environments, i.e. high stress, low rock mass strength, etc. The 4-way intersections of the El Teniente layout are less stable than those of the Cube layout due to the orientation of the drawbell drives and the size of the pillars. The oblique orientation of the Drawbell drives leads to the El Teniente layout having an elongated pillar nose and the narrow pillar is offset to the principal stress direction. As such the pillar geometry of the El Teniente has been shown to be more susceptible to pillar instability in adverse conditions compared to the Cube design with its larger and more regularly shaped pillars. The development strategy of the Extraction Level can further reduce the impact of the intersection geometry by allowing pre-supporting to minimize any damage and also reducing the number of intersections that are “turned out” using stripping along the Extraction Drive and instead developing along the drawbell drive and through the intersection with the Extraction Drive.

The drawbells in the Cube design are considerably larger than the current Major and Minor Apex pillars in an El Teniente layout. As such these large rock pillars can accommodate variability and structures in the rock mass much better than the current pillars

The inclined section in the upper portion of the drawbell, which is fired as downholes from the Undercut level, does have large faces compared to the current industry standard drawbells. As the Cube drawbell is fired in multiple sections, to manage the establishment area and thus the associated seismic energy release and the amount of rock that can swell to fill the void in the drawbell, this is perceived to minimize the risk of strain bursting on the exposed faces of the drawbell. If bursting were to occur on the rock faces it would likely only eject the rock into the drawbell, which will be choked with blasted or caved material depending on when the burst occurred. Electronic detonators are also planned to be used in the drawbell blasting to ensure the accurate timing of initiation and therefore minimise the release of energy associated with opening the drawbells.

The faces of the drawbell may spall and wear over time as the ore is recovered from the drawbell but this is compensated for in the significantly larger than existing pillars of rock between the drawbells.

Further work is required to analyse the changes in stress conditions across the Extraction Level and through the pillars as the cave is established. The stability modelling work completed as part of this thesis indicates that the pillar geometries are stable during the establishment of the cave, though they do not specifically analyse the stages of cave establishment on the footprint.

5.1.6 Ore Recovery Impacts

The stability assessments completed show that the Cube design is considerably more stable than a large contemporary El Teniente layout. The improved drive deformation results in limited to no Extraction Level area losses, Drawpoints and/or Extraction Drives, which has a positive impact on the future ore recovery estimates from the flow simulations to be completed in the next section. The level stability of the Cube layout results in fully available drawpoints with limited rehabilitation requirements and enables the execution of the preferred draw strategy across the footprint.

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. Those access issues result in compounding operational impacts as static draw columns lead to additional cave load transfer on the Extraction Level pillars. As neither the timing of the drawpoint access issues, nor the compounding cave load issues, can 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.

There are considerable operational and productivity impacts from failing or failed Extraction Drives and drawpoints through the life of an Extraction Level. Failing areas not only require rehabilitation resources but also impact on the number of drawpoints available for production and may also impact the LHD tramming routes, infrastructure (including, communications, raw water, dewatering and roadways) and ventilation flows. There comes a time when the rehabilitation and damage impacts become too great and part or all of the Extraction Level is abandoned, when this happens a Recovery Level below the impacted area may be established to recover the remaining material from the cave. The draw from the Recovery Level is compromised by the infrastructure installed on the original Extraction Level and the recovery of the remaining ore is compromised and far from guaranteed.

Chapter 6

6 Flow Modelling

6.1 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.

For over 50 years, granular flow in caves has been studied and scale model experiments conducted to improve our understanding, resulting in theories which still form the basis of modern cave design. In recent years though, these theories are being challenged as the mining environments are deeper, in more competent rock masses and the layouts considerably larger. Some operations have conducted full-scale experiments which have produced results leading to new theories on cave draw including ‘disturbed flow’. Though due to the lack of measurements from the modern mines the older empirical guidelines are still widely used today.

6.1.1 Flow Code Review

There are currently several computer-based flow estimation codes (Table 2) utilised in the industry. These flow models can be utilised to understand a number of caving and flow characteristics including rilling, subsidence and grade forecasting, Figure 68.

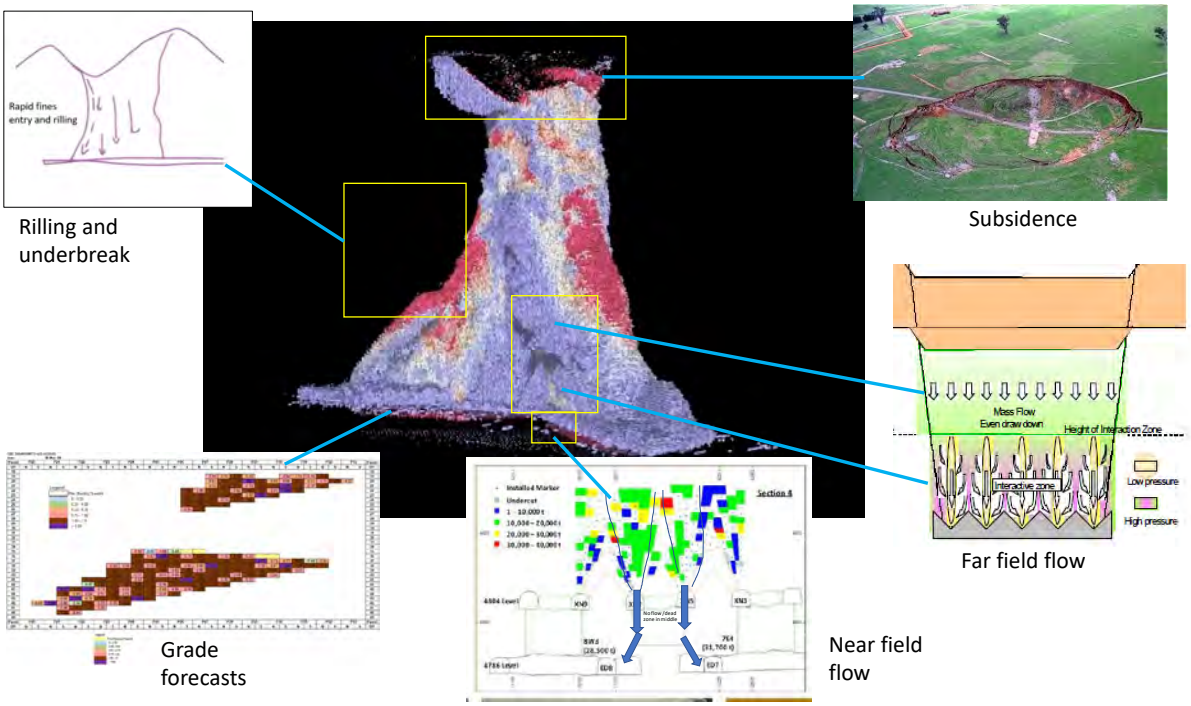


Figure 68: Components and outputs of Computer flow models

Table 2: Flow Code model comparisons

Caving / flow behaviour	Template mixing	Cellular automata (uncoupled)	Cellular Automata coupled with finite element stress model	Physics based flow coupled with finite element stress model
Flow mechanism	Stochastic	Stochastic	Stochastic	Physics based particle kinematics
Example Product	PCBC	PGCA	CaveSim	FS4
Cave growth	Not included. Draw = cave propagation	Cave shapes can be included to enable draw down and airgap formation. Requires cave shapes from FE model	Cave drawdown and cave propagation evolve in small model steps	Cave drawdown and cave propagation evolve in small model steps
Cave shape influence on drawdown	Not possible	As above	Yes	Yes
Cave stall / Airgap prediction	Not possible	Not possible	Yes	Yes
Subsidence	Not possible	Not possible	Yes	Yes
Rilling	Not possible	Some rilling possible	Rilling partially simulated in model, but limited in the stochastic CA framework	Rilling occurs based on particle physics
Isolated draw (near field)	User defined draw zone/width	User defined draw zone/width	User defined draw zone/width	Draw zone dimensions determined by particle interaction
Mass flow (far field)	User defined draw zone/width	User defined draw zone/width	User defined draw zone/width	Yes. Draw interaction and mixing occurs high in the cave muckpile based on cave draw and particle to particle interaction
Grade tracking / forecasting	Yes	Yes	Yes	Yes
Fines flow	User defined setting for fines	User defined setting for relative velocity of “fines” material in block model	User defined setting for relative velocity of “fines” material in block model	In development
Drawbell and undercut design impacts flow behaviour	Not possible	Yes, but limited to numeric input settings. 3D geometry not included	Yes, but effect is limited due to user defined draw zones	Yes
Overburden pressure in the muckpile (impacts footprint loading and cave flow)	Not possible	Not possible	Not possible	Yes
Pillar loading due to overburden pressure and cave draw schedule	Not possible	Not possible	Not possible	In development
Water flow in muckpile	Not possible	Not possible	Not possible	In development
Simulation of variable particles sizes	Not possible	Not possible	Not possible	In development
Simulation of hang-ups and hang-up frequency	Not possible	Not possible	Not possible	In development

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 early physical models.

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 utilised 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. To confirm the base logic of the models calibration checks were undertaken against the original sand model experiments and when the results were shown to be a match for those previously observed the flow analysis scope was completed.

6.1.2 FS4 Inputs

Beck Engineering's (BE) FS4 flow code is a Position Based Dynamics (PBD) method utilising physics-based particle to particle simulation that has replaced previous stochastic flow simulators used by BE for the past 10 years. FS4 includes particle to particle kinematics and dynamics which enables a higher resolution and differentiation between flow courses of action that were not possible with the stochastic flow codes.

(Campbell 2020) states that FS4 is a Position Based Dynamics method (PBD) (Muller 2006, Kloss 2012, Bender 2014, Macklin 2014). Recent improvements of the algorithm as the extended position-based dynamics (XPBD) algorithm proposed in (Macklin 2016). The use of such numerical methods maintains the basic idea and advantages of the DEM methodology. However, PBD based methods provide significant advances in terms of computational efficiency and provide the power to solve large particle flow based problems, such as those in cave mining. The ability to simulate problems with many millions of discrete particles where the particle interaction and dynamics can evolve freely under gravity, and unstable flow processes allows the integration of such an algorithm into a coupled flow-deformation modelling framework. The nature of flow and the resulting muckpile inside the cave evolves from the constitutive properties of particles. The PBD method for simulating cave flow and muckpile shape can now be used to replace the NCA component for coupled simulations.

The FS4 flow code has been utilised by Freeport for a number of years with onsite calibration of the code via drawpoint sampling and mill reconciliations improving the

predictions over time. Glencore have also utilised the code at the Ernest Henry SLC Mine with satisfactory results and ongoing calibration.

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 was 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 layout. These were the same properties used in the stability modelling as outlined in Chapter 5.1.2. Figure 69 shows the location of the sub model within the larger Freeport Deep Ore Zone (DOZ) footprint. The comparative drawbell layouts used in the FS4 model for the Cube and the El Teniente designs are shown in Figure 70 and Figure 71 respectively.

Approximately 40 simulations were completed as part of this research, the most important models for the assessment of flow in the new layout are shown in Table 3 with results of the highlighted options discussed below.

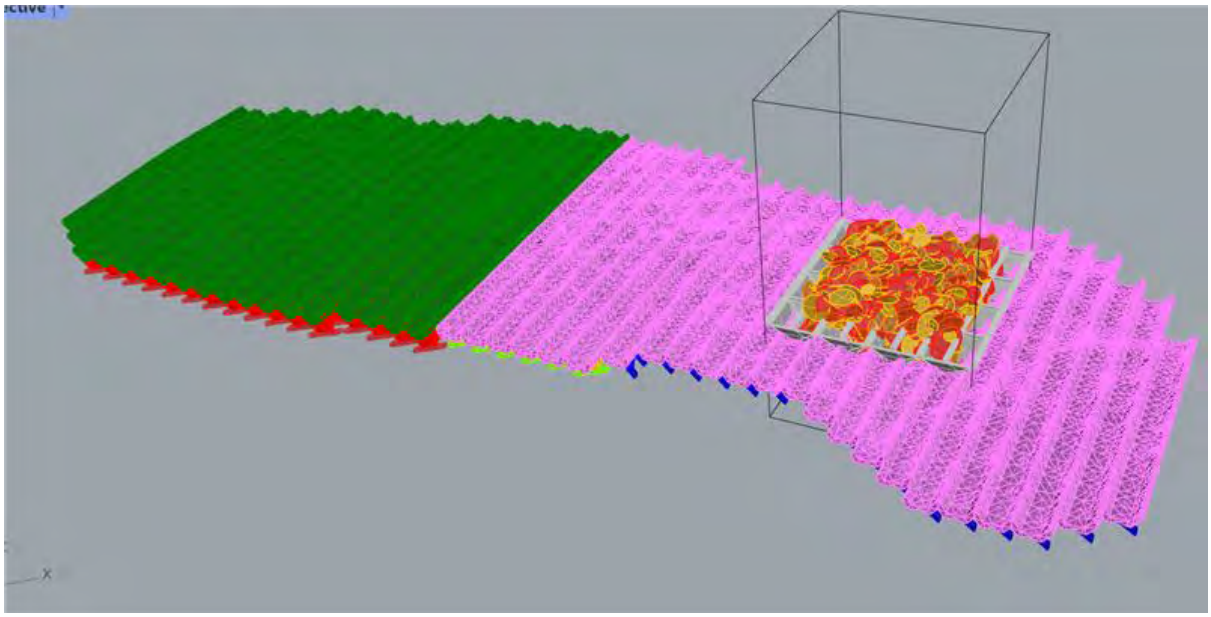


Figure 69: Sub model location within the DOZ Footprint

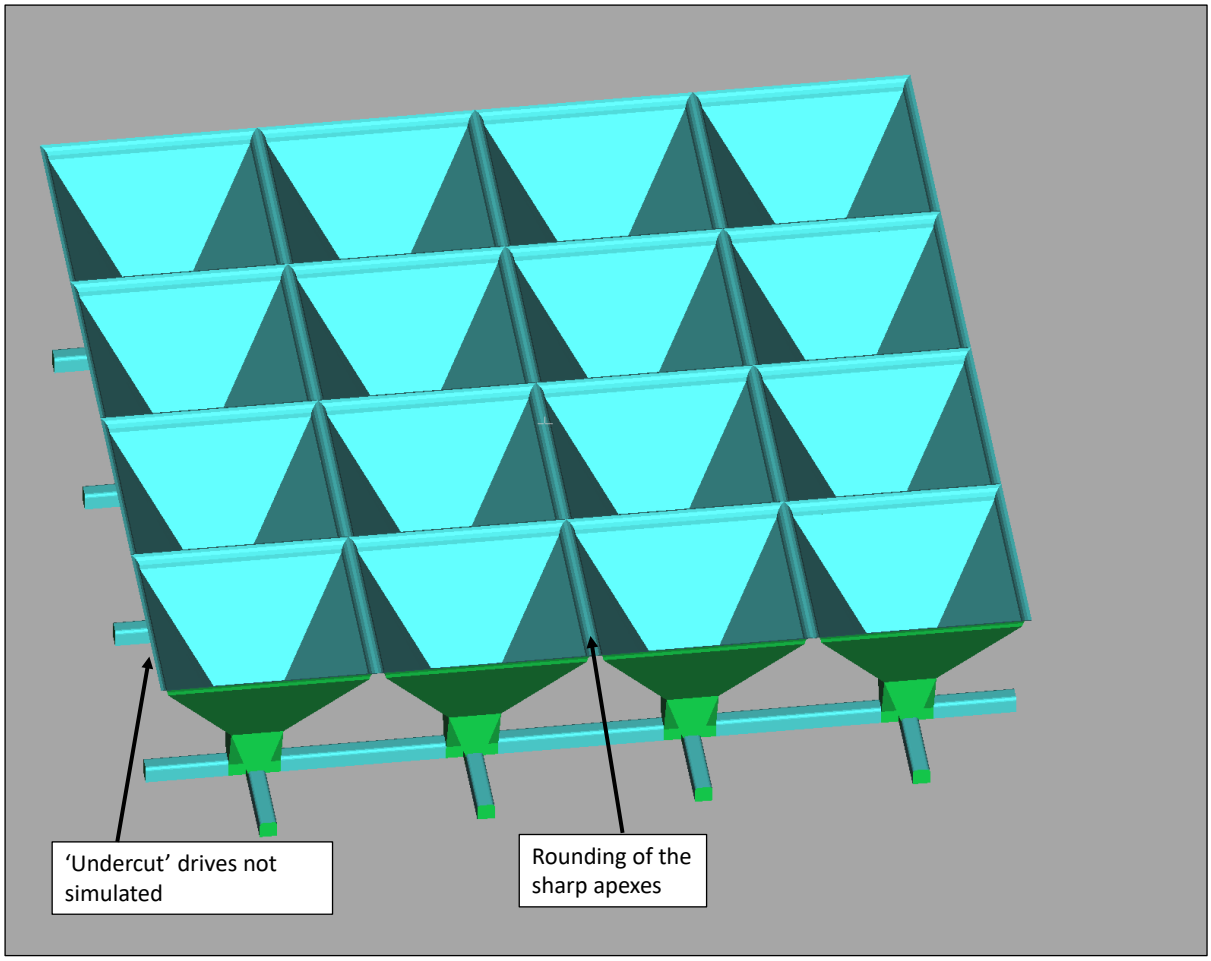


Figure 70: Cube drawbell design used in the FS4 model

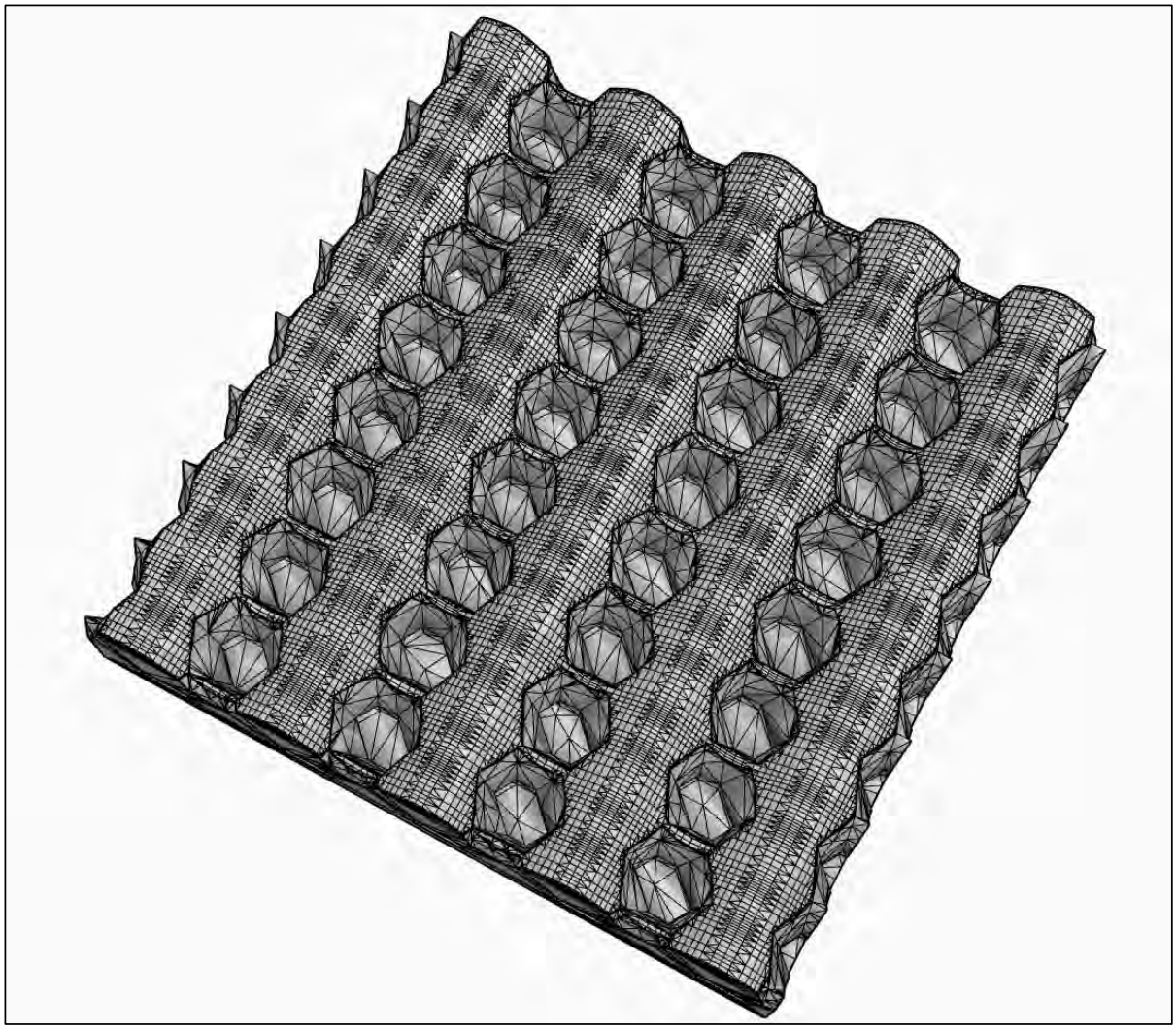


Figure 71: 18m x 30m El Teniente drawbell design used in the FS4 model

Table 3: FS4 Model runs

Run name / number	Drawbell spacing	Footprint size (# DB's)	particle box dimensions	Drawn tonnes	Draw simulation type/ draw increments	Single or clumped particles	Particle radius
R13_R01	16x30m	36 db total, 2 dp per db	x=150, y=150, z=270	6,749,400	random draw like R20, scaled to smaller footprint. 7 active drawpoints per period.	Single	0.5
R25Large_R01	18x30m	28 db total, 2 dp per db	x=150, y=150, z=270	6,749,400	random draw like R20, scaled to smaller footprint. 7 active drawpoints per period.	Single	0.5
R25Small_R01	18x30m	32 db total, 2 dp per db	x=150, y=150, z=270	6,750,000	random draw like R20, scaled to smaller footprint. 6 active drawpoints per period.		
Telfer_SS_R01	17x38m	36 db total, 2 dp per db	x=150, y=150, z=270	6,749,400	random draw like R20, scaled to smaller footprint. 7 active drawpoints per period.		
R24	50m x 50m	Single DB sim using the same mesh as R20	x=200, y=200, z=270	2,000,000	1 drawbell drawing 10000 tonnes per period, 200 periods.	Single	0.5
single_drawbell_design_comparison_R24_3x3	50m x 50m	Single DB sim using 3DBx3DB mesh	x=150, y=150, z=270	1,000,000	1 drawbell drawing 10000 tonnes per period, 100 periods.	Single	0.5
single_drawbell_design_comparison_R13	50m x 50m	Single DB sim using 3DBx3DB mesh	x=150, y=150, z=270	1,000,000	1 drawbell drawing 10000 tonnes per period, 100 periods.	Single	0.5
single_drawbell_design_comparison_R25Large	50m x 50m	Single DB sim using 3DBx3DB mesh	x=150, y=150, z=270	1,000,000	1 drawbell drawing 10000 tonnes per period, 100 periods.	Single	0.5
single_drawbell_design_comparison_R25Small	50m x 50m	Single DB sim using 3DBx3DB mesh	x=150, y=150, z=270	1,000,000	1 drawbell drawing 10000 tonnes per period, 100 periods.	Single	0.5
single_drawbell_design_comparison_Telfer_SS	50m x 50m	Single DB sim using 3DBx3DB mesh	x=150, y=150, z=270	1,000,000	1 drawbell drawing 10000 tonnes per period, 100 periods.	Single	0.5
R24_3x3_high_res_1dz_large_drawzone	50m x 50m	small particles (r=0.25) version of R24_3x3					
R24_3x3_high_res_1dz_small_drawzone	50m x 50m	same with above, but smaller drawzone					
R24_3x3_high_res_2dz	50m x 50m	same as above, but alternatingly drawing out of two					
R24_3x3_high_res_4dz	50m x 50m	same as above, but alternatingly drawing out of four tunnels					
R25_Large_high_res	50m x 50m	small particles (r=0.25) version of R25_Large, alternating					
R30	50m x 50m	rerun of R09 with new params; mesh with blunt top					0.5
R31	50m x 50m	rerun of R10 with new params; mesh with blunt top					0.5
R32	50m x 50m	rerun of R09 with new params; normal 4x4 mesh					0.5
R33	50m x 50m	rerun of R10 with new params; normal 4x4 mesh					0.5
R34 (R20 rerun)	50m x 50m	4 DB x 4 DB (16 in total), 4 dp per db	x=200, y=200, z=270	12,000,000	6 random active drawpoints per period, 10k tonnes per drawpoint/per period, 200 periods	Single	0.5
R35	50m x 50m	rerun of R09 with new params; normal 4x4 mesh					0.5
R36	50m x 50m	rerun of R10 with new params; normal 4x4 mesh					0.5

6.1.3 Overview of Model simulations

There were two scales of models developed using the Beck Engineering FS4 flow software to assess the flow properties of the Cube and the comparative El Teniente layouts.

The first was a small scale model to simulate:

- material flow at a drawbell scale for the El Teniente layout with an 18m x 30m drawbell spacing
- material flow at a drawbell scale for the 50m x 50m Cube design,
    - 2 drawpoints drawn, to model likely loading strategy on the Extraction Level and to compare to the existing 2 sided drawbells,
    - 4 drawpoint draw scenarios, and
    - Single draw zone in the middle of the drawbell.

The objectives of the simulations were:

- Early recovery and flow patterns at a drawbell scale,
- Assess the effects of different drawpoint draw scenarios and flow mechanics.

The second was a large scale model to simulate:

- material flow at a mine scale for the El Teniente layout with an 18 x 30m drawbell spacing on a 7 x 7 drawbell pattern utilising randomized draw patterns,
- material flow at a mine scale for the 50m x 50m Cube design on a 4 x 4 drawbell pattern utilising random draw patterns.

The objectives of the simulations were:

- Assess flow patterns and the evolution of Movement and Extraction zones for variable draw from multiple drawbells,
- Assess regions of isolated draw and the heights of interaction, if any,
- Compare the flow patterns for draw from 1, 2 and multiple drawpoints to show the impact of the multi-drawbell draw in an operating cave mine,
- Compare recovery patterns for a contemporary footprint design and the Cube design.

Whilst the software is capable of simulating hang-ups or hang-up frequency this was excluded from the scope of modelling for this thesis. It is an area for further research in the future.

6.1.4 FS4 Flow Results

The main findings of the drawbell flow modeling were:

- The Extraction zones and Movement zones in the flow model forecasts are well matched to previous measurements in the literature and kinematic flow theory, Figure 72.

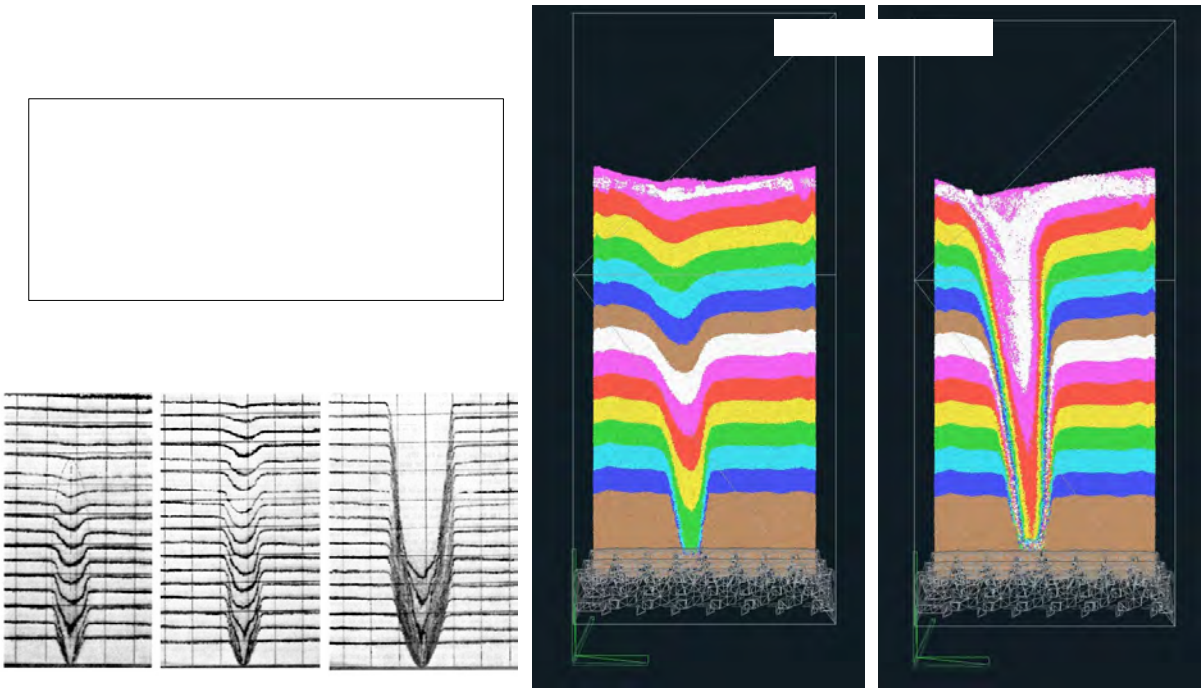


Figure 72: Movement zone comparison of sand models and FS4 simulations

- The flow forecasts for the El Teniente (Figure 73) and Cube (Figure 74) designs have a taller & thinner draw zone than some scale measurements and kinematic theory. This is likely due to the high vertical confinement in the model which causes the draw zone to be narrower as noted by Peters (1984) and Yenge (1981).

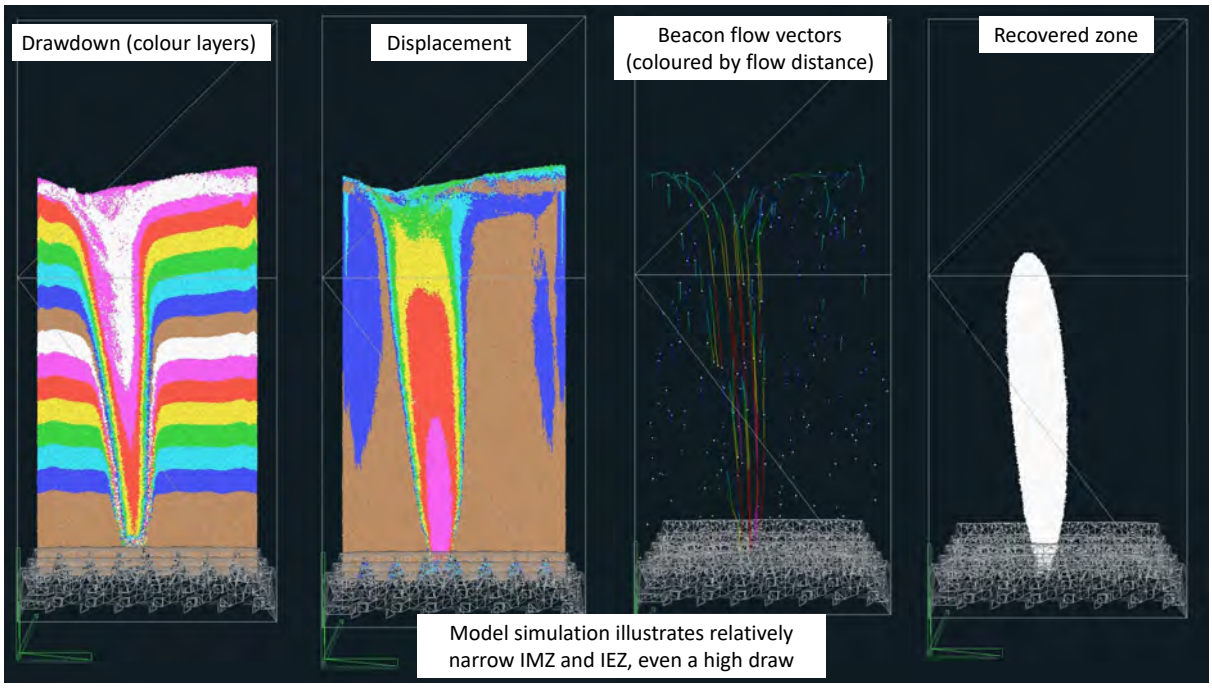


Figure 73: Model simulations of single El Teniente layout Movement and Extraction zones

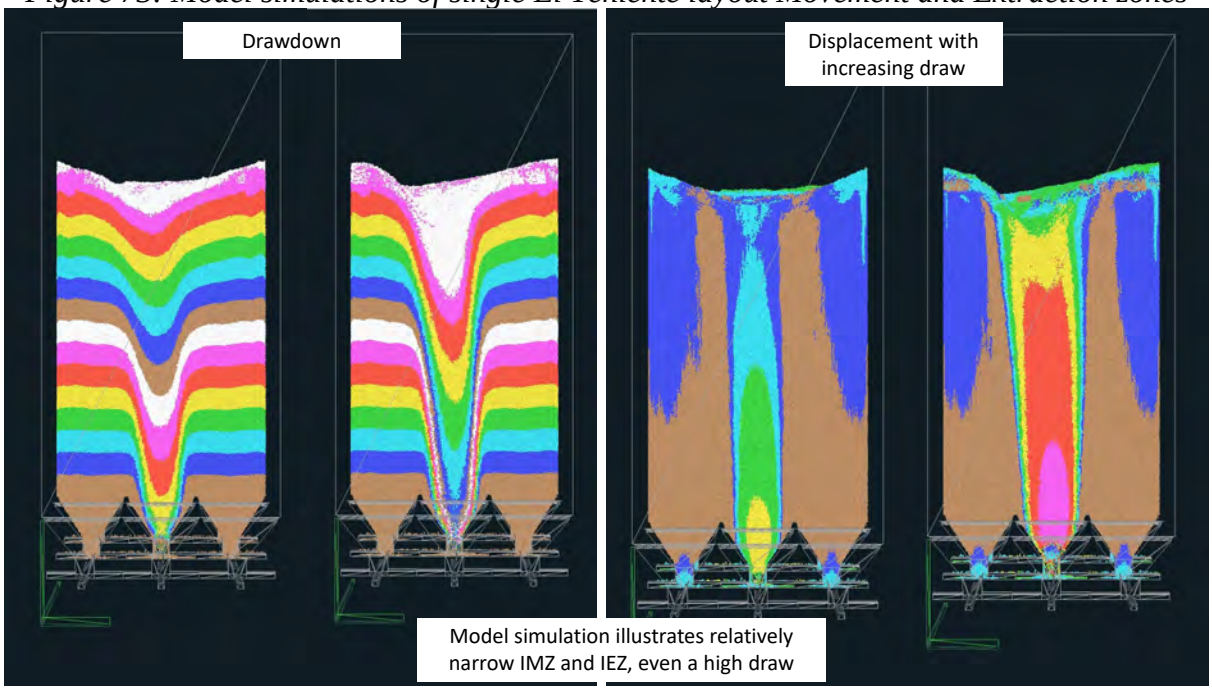


Figure 74: Model simulations of single Cube Movement and Extraction zones

- The movement zone height and width are significantly controlled by the lower drawbell geometry during early draw (Figure 75).

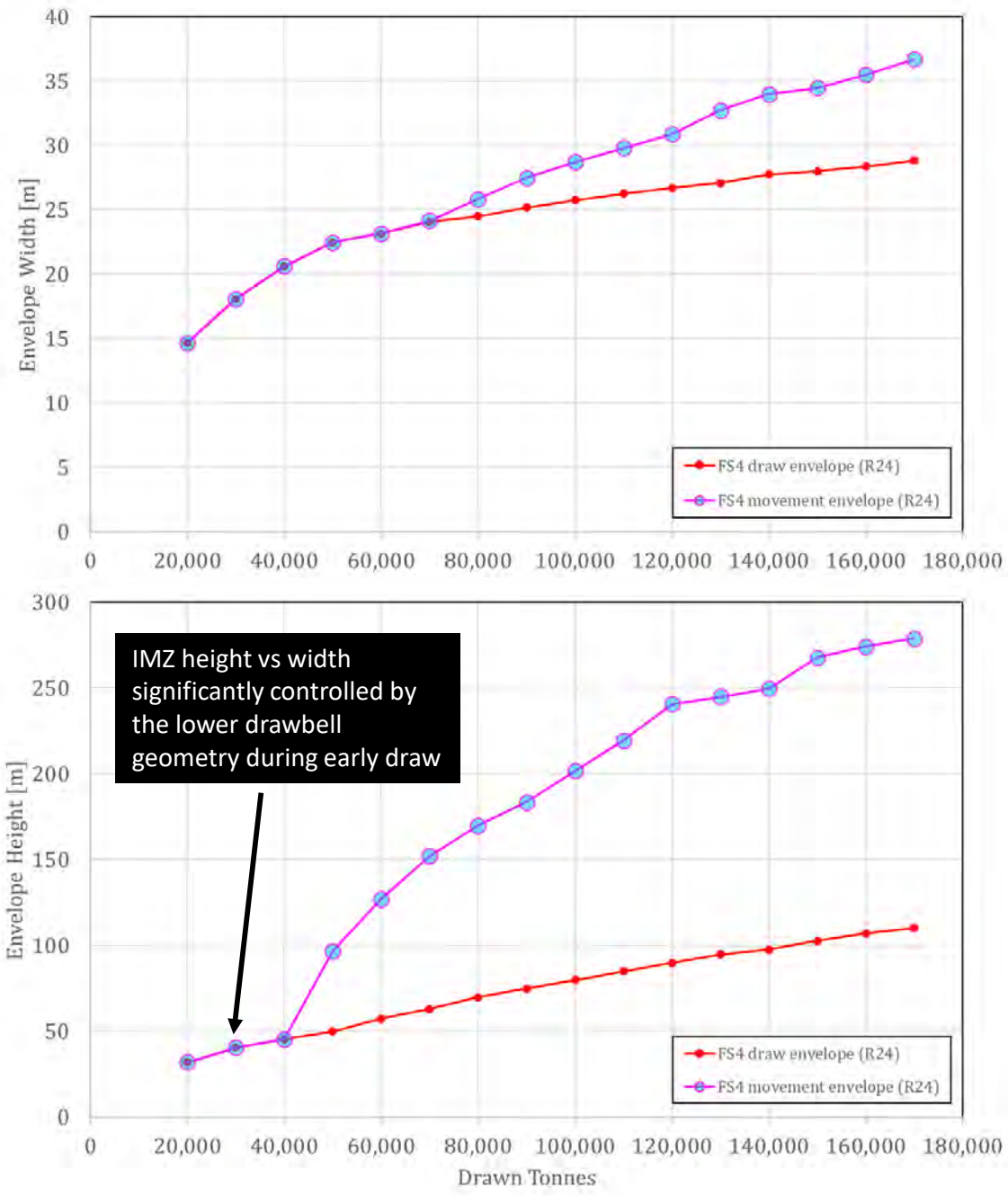


Figure 75: Drawbell geometry effects on the Movement Zone

- The modeling indicates a low flow/dead zone is formed in the middle of the drawbell, in between the draw zones from each drawpoint. This is consistent with underground observations in 2 sided drawbells (Figure 76 and Figure 77).

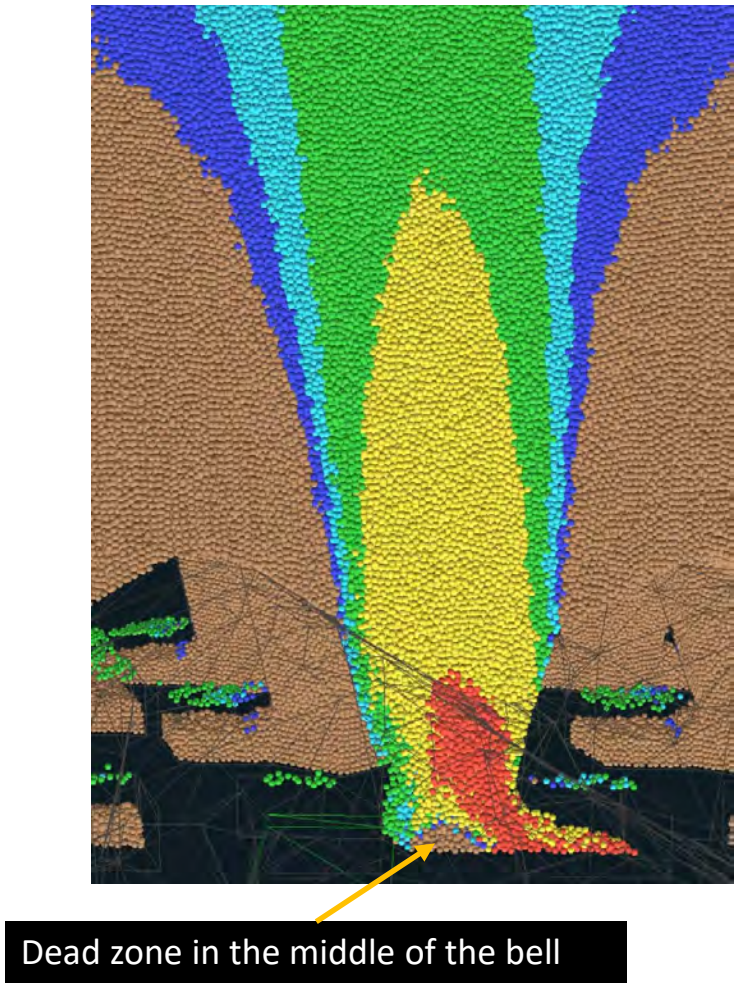


Figure 76: Particle displacement in an El Teniente drawbell

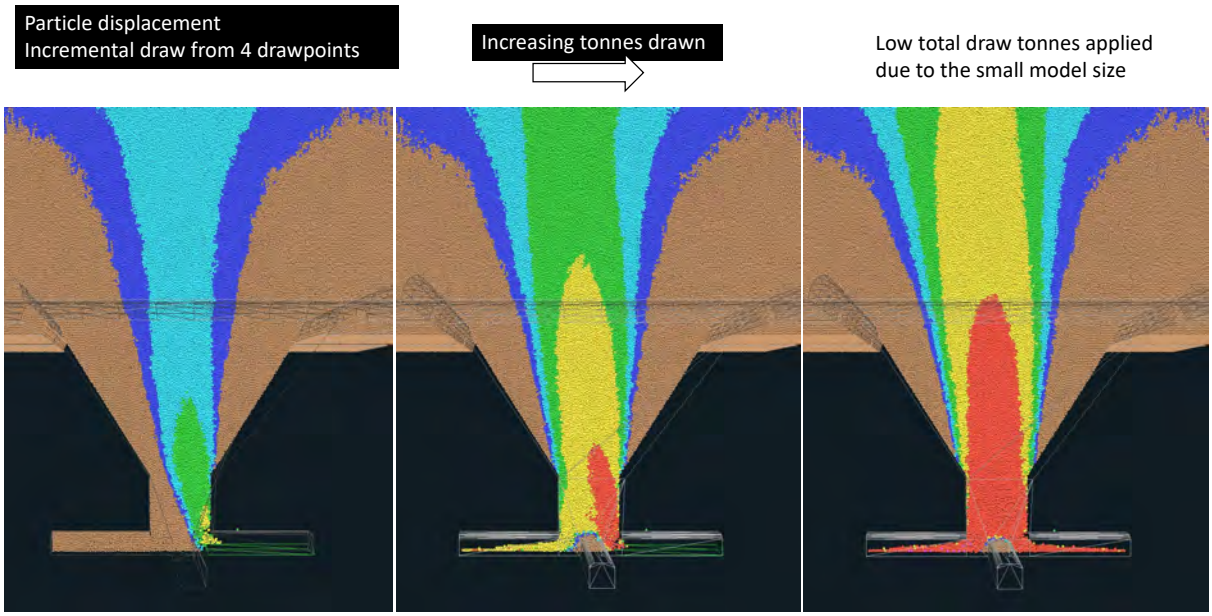
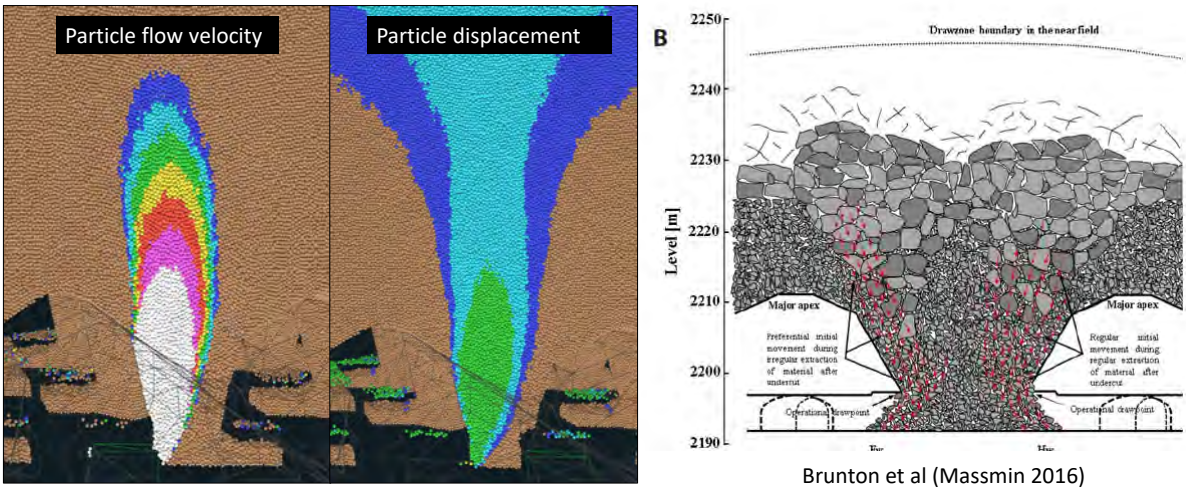


Figure 77: Particle displacement in a Cube drawbell

- The width of the extraction zone for a single drawbell increases to almost 30m when all four

drawpoints are in operation, Figure 75.

- The movement zone continues to widen incrementally with increased draw, Figure 75. This is matched by the observations of (Power 2004) and a large physical model. This was termed the "erosion" effect.
- The flow modeling of a 30 x 18m El Teniente drawbell demonstrated flow characteristics in line with the observations of (Brunton, Lett et al. 2016), Figure 78.

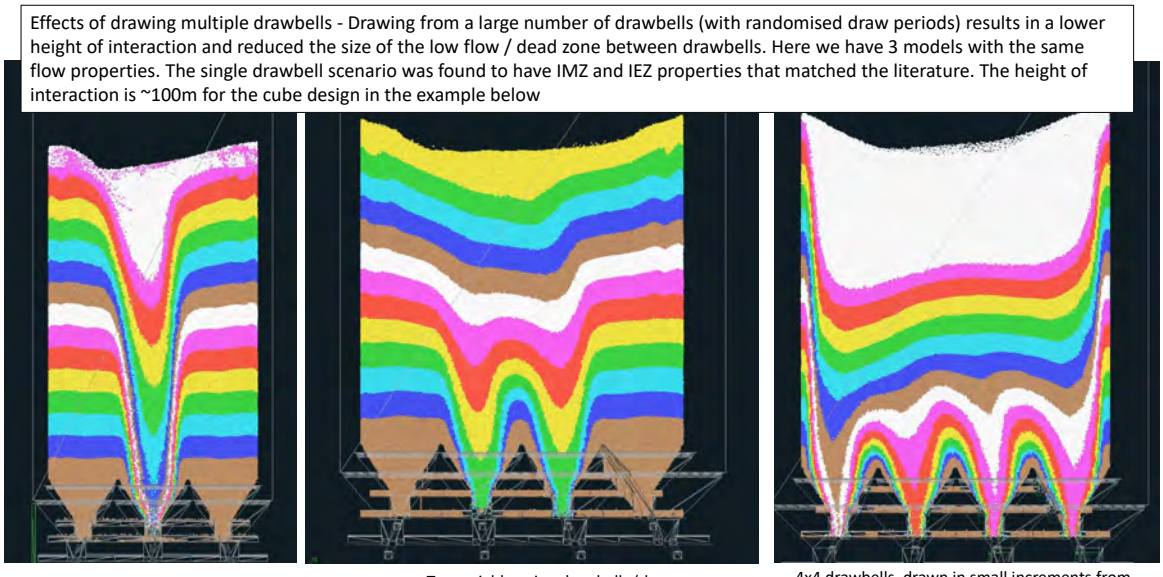


Brunton et al (Massmin 2016)

Figure 78: Flow model comparison to (Brunton, Lett et al. 2016) observations

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 79. The size of the low flow zone is similar for both incremental alternate draw as well as continuous draw flow simulations.



Single drawbell

Two neighbouring drawbells (drawn alternatively)

4x4 drawbells, drawn in small increments from random drawpoints in each step. Same total draw at end of model for each bell

Figure 79: Low flow areas between drawbells

- The two drawbell simulations demonstrated similar flow patterns to the sand models by Marano (1980) as shown in Figure 80. Additional simulations where the upper 20m of the apices in the Cube design were flattened showed similar results to the modified sand models, indicating the importance of drawbell geometry on ore recovery.

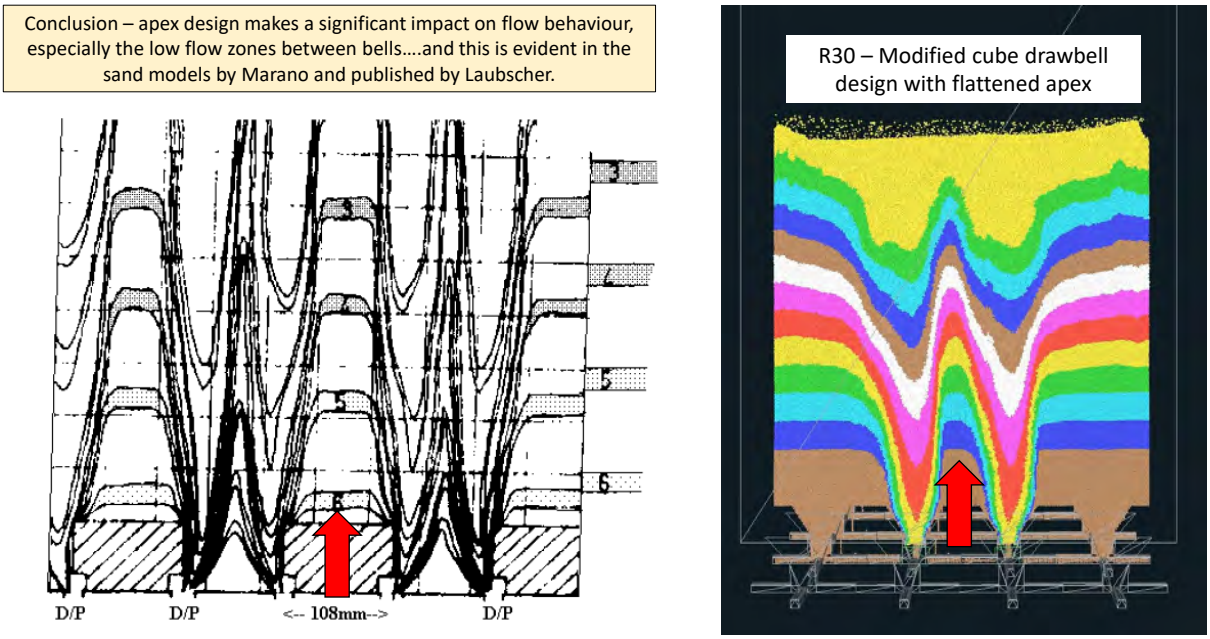


Figure 80: Influence of Apex design on flow zones ((Laubscher 1994)

- Drawing from a large number of drawbells in a 4 x 4 drawbell arrangement, 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/dead zone area between the drawbells. The height of interaction for the movement zones is ~100 to 150m for the Cube design and the height reduces as the cave matures and is drawn down, mostly due to the progressive widening of the movement zones due to “erosion” effects. These remaining low flow zones are across the diagonal axis between the drawpoints of offset drawbells as shown in Figure 81.

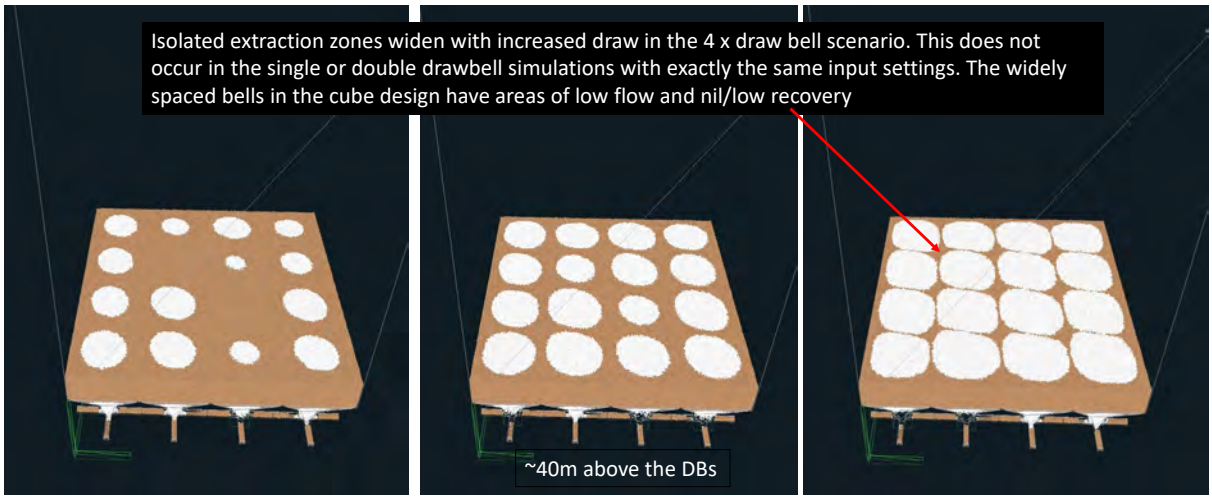


Figure 81: Progressive Extraction Zones for the Cube Layout

- There is a more vertical flow estimate on the edges of the models from the Cube layout than for the El Teniente layout, see Figure 82.

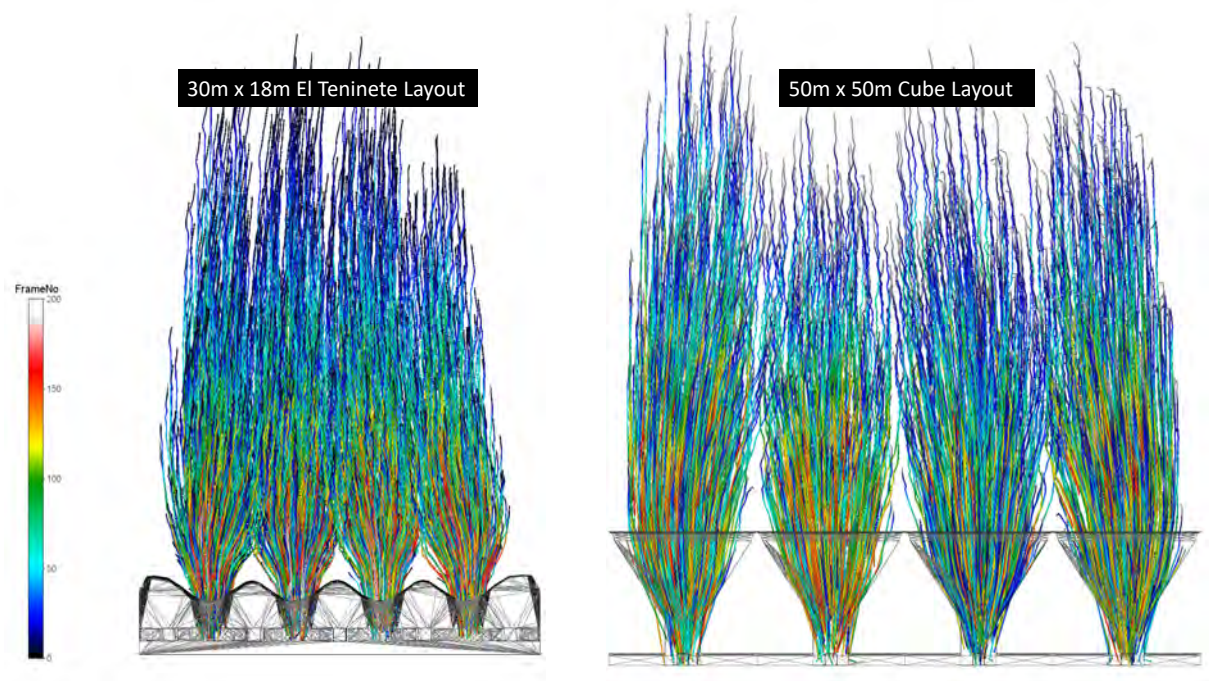


Figure 82: Edge draw comparisons

6.1.5 Flow Code limitations associated with the FS4

Whilst the FS4 flow code is potentially the most advanced computer simulation code for flow available, it still has limitations which influence the results. The key limitations of the code currently are:

- It utilises a single particle size in the simulations, as such, the effects of fines material or secondary breakage of cave fragments are not included in the modelling done to date.

- The flow models are not constrained by cave shape or cave back geometry. This would result in more rilling effects as well as additional mixing of the cave columns compared to the idealized flow model where material is assumed to be broken and available to be drawn.
- There are limited marker trials available for model validation, this includes the few mines that have installed beacons to track material flow paths throughout the cave lift height.
- Height of interaction is not extensively measured in block caves. Some beacon trails demonstrate the variability in cave flow, including mass flow, chimneying and rilling, however widespread characterization of cave flow throughout a block cave lift has not yet been completed.

6.1.6 Scalability and Design Influencing Factors

As the FS4 flow simulator utilises 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 model is run in two stages with a near-field or small-scale model run to estimate the draw inside and within the vicinity of the drawbell. This model is constructed with small particle sizes to determine the key shape parameters for the draw columns and to identify any impediments to the preferred draw shape by the drawbell geometry. The second stage of the modelling is a larger scale far-field model investigating the interaction of the various drawpoint draw columns based on the near-field model parameters. The far-field model is then run utilising a random draw pattern to simulate the variable nature of actual draw strategies from drawpoints across the footprint.

When the model is run for the far-field simulations the extraction is from a single point in the centre of the drawbell with the near-field results used to define the shape of flow inside the drawbell. This far-field modeling simplification enables the model to run but does deviate from the expected draw column geometry of the 4 draw locations in the Cube design, and even the 2 draw locations in the El Teniente layout. The impact is likely a narrower far-field draw column prediction than will occur in reality.

6.1.7 Impact of Draw Strategy on Flow Results

The modeling indicated that there was a wider movement zone generated when a multiple number of drawbells were actively loaded from in the given time periods, than if just a single drawbell is active. The more material extracted from a drawpoint increased the width of the movement zone through the

"erosion" effect, which also lowered the height of interaction between the drawpoints.

6.1.8 Conclusions from the Flow and Recovery Results

The key recommendations from the Beck Engineering team to improve the flow and ore recovery of the Cube layout were:

- Test alternate drawbell spacing to reduce the impact of the low flow areas on the diagonal axis between the drawbells. The proposed 50m x 50m spacing is considerably larger than any of the contemporary layouts and results in a diagonal spacing of ~71m
- The Cube design has significant benefits for stability compared to the contemporary El Teniente Block Cave design. A recommendation to reduce the spacing of the current design to find a potentially better balance between the stability and ore recovery trade-off.
- The distance between the drawpoint brows in the drawbell could be widened as the current spacing of 12m is resulting in very good draw interaction of the 4 drawpoints within the drawbell. By widening this internal drawpoint spacing the overall Movement and Extraction zones should increase, further improving recovery.
- Further "shaping" of the drawbell may improve the flow in the near field.
- The length of the drawpoint ensures that the LHD enters the muckpile at a right angle and loads from either side of the drawpoint enhancing the near field ore recovery and thus the far field recovery of the ore. This approach to the drawpoint rill is a function of the perpendicular layout and the short tramming distances of the LHD.

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.

The Cube layout with its order of magnitude stability increase has only one area of concern, due to it being theoretical, and that is the actual flow and extraction from the drawpoints within the 4-sided drawbell. Utilising the latest computer modelling software, in the same way that the stability analysis has been completed, indicates that the ore recovery of the Cube layout is comparable to an idealized 30m x 18m El Teniente layout.

In this chapter it has been shown that the Cube layout has no detrimental impacts on ore recovery, subject to the acknowledged model limitations, when compared to a 30 x 18m El Teniente layout and further the Cube layout has superior stability when compared to a larger 30 x 24m El Teniente layout.

Therefore, from a technical perspective there are no fatal flaws in the proposed design. As such the next chapter will investigate the Management and Operational advantages of the proposed design.

Chapter 7

7 Management and Operating Systems

7.1 Extraction Level Establishment

7.1.1 Cave Establishment Logic

Through the redesign of the Extraction Level to a series of parallel and crosscutting drives, Figure 83, the level can be efficiently developed using existing “long” round boring jumbos such as the Sandvik 442i (taking a >6m cut) or rock cutting machines, such as the Komatsu MC51 should they prove to be capable and cost effective. The total metres of development required within the nominal orebody of 350m x 200m to establish the caving footprint of the Cube layout on a 50m x 50m spacing is approximately 15% less than that for the El Teniente layout on a 32m x 22m spacing as provided by Newcrest that represents the Cadia East Panel Cave 2 Stage 3 layout (5,100m and 5,850m respectively). The ability to develop the Cube layout in consistent straight headings across the footprint, including mining through intersections, allows for all but the first few turn outs to establish the headings being completed by the long round jumbo with supporting jumbos installing the ground support, thus significantly reducing the number of cuts required to establish the footprint (~950 cuts vs ~1,240 cuts or a 25% reduction).

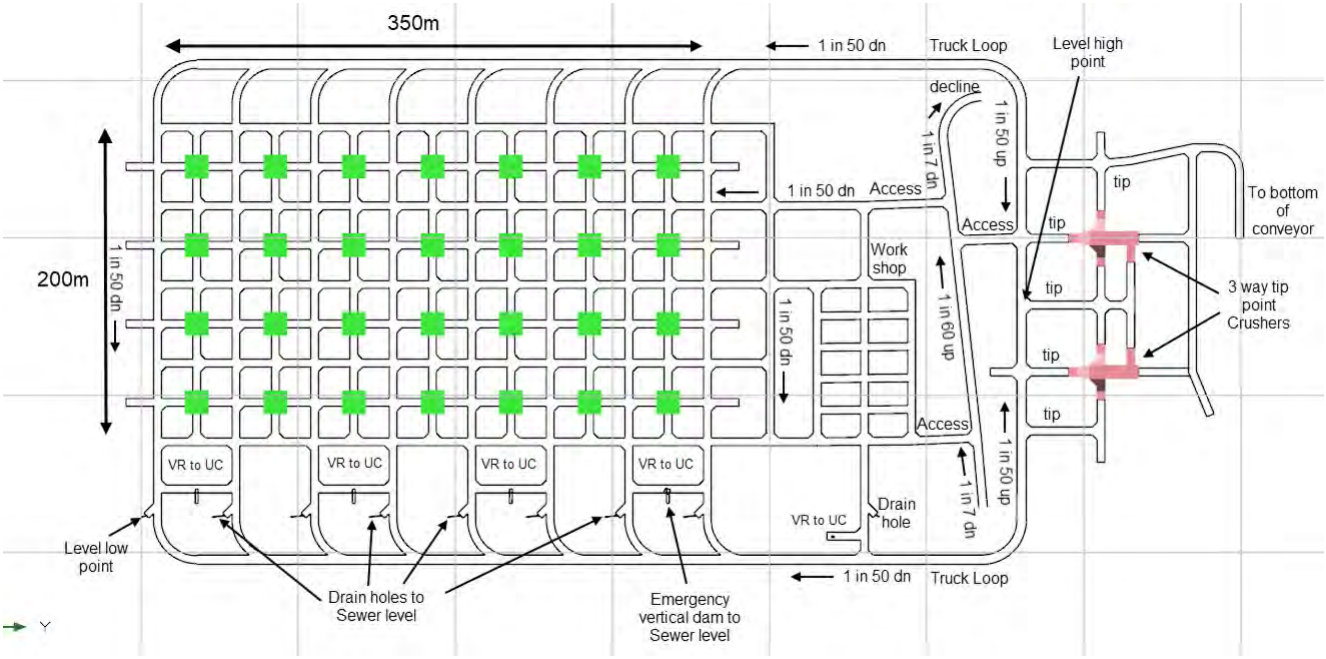


Figure 83: Extraction Level design for Cube Layout

To manage the stress levels being experienced, and forecast, at depth the current caves and projects are predominantly utilising an advanced undercutting strategy with a Large W undercut geometry to protect the Extraction Level development through the cave establishment phase to provide the most stable tunnels for future production. A significant downside to the Large W undercut is the additional Apex level which acts as a socket drive to provide relief for the undercut blasts and requires double the development and additional ventilation allocation to establish. The impact of utilising an advance undercut sequence is that only the Extraction Drives can be established ahead of the undercut front on the Extraction Level. The Drawbell Drives are only commenced once the undercut face has passed over their starting location to protect the intersection span about to be created. So, whilst the El Teniente layout also contains straight development tunnels, most of the Drawpoint Drives require individual establishment via small stripping cuts to protect the pillars which are created between the parallel Drawbell Drives when an advanced undercutting sequence is used, as at Rio Tinto's Oyu Tolgoi project in Mongolia and New Gold's New Afton mine in Canada. Also, the oblique geometry of the drawpoint drives to the Extraction Drives creates a larger 4-way intersection than if they were perpendicular turnouts. The drawpoint drives are also oblique to the undercutting front making the initiation timing the result of a complex set of predecessors.

Should the El Teniente layout be utilised with a Post Undercutting strategy then many of the drawbell drives can be mined continuously through the intersections with the Extraction Drives significantly reducing the number of cuts required to establish the footprint. From personal experience one of the key issues with the current El Teniente layout at depth, even with the larger drawbell spacings of 32m x 20m or even 34m x 22m, is that the narrow pillars created between the Drawbell Drives and the

Extraction Drives cannot withstand the abutment loads when the drawbell has been fired in front of the undercut face, in a Post Undercutting sequence, resulting in collapsed tunnels which require either significant rehabilitation or abandonment which impacts the cave establishment phase of the footprint and potentially results in the abandonment of the Extraction Level. From experience at Cadia East PC2S1 and PC2S2 the pre-established pillars of the El Teniente layout failed and the undercutting strategy was converted to an Advanced sequence which required a full redesign of the undercut geometry and firing sequence delaying the full establishment of the level by months.

The larger pillars around the Extraction Level tunnels in the Cube layout allows for the Post Undercutting sequence to be used, even at greater depths than are currently being planned for. The post undercutting sequence enables checking of the drawbell shape post firing to ensure full break out, as the drawbell is essentially just a small stope above the drawpoint drives, prior to firing the undercut into it. By firing the drawbell first there is a larger void available to fire the undercut into, further reducing the risk of creating pillars in the footprint through poor blasting practices. The larger undercut firings also reduce the total number of firings required to establish the caving footprint (~168 firings vs 440-880 for an El Teniente) which reduces the exposure time of personnel to the caving front and influences the amount of exclusion time to allow the rock mass to resettle after an undercut blast. These factors materially increase the rate at which the caving footprint can be established, within the individual rock mass seismic response limits, and therefore significantly reducing the exposure time of the footprint to the caving induced stresses created when undercutting a rock mass.

The Cube layout allows for the paralleling of many tasks on the Extraction Level and also relocates much of the drilling required to establish the drawbell to the Undercut Level, a series of parallel drives on 50m centres traversing the mining block (Figure 84), thus further reducing the congestion on the Extraction Level (Figure 83). With the 4-way access to each drawbell, the additional accesses allow for tasks to continue in the establishment of the drawbell even if two of the accesses are blocked due to certain tasks, i.e. concreting of the access or drawpoint brow installation, being undertaken. This flexibility ensures that Extraction Level establishment works can continue without impediment creating a level of contingency not available to the El Teniente design.

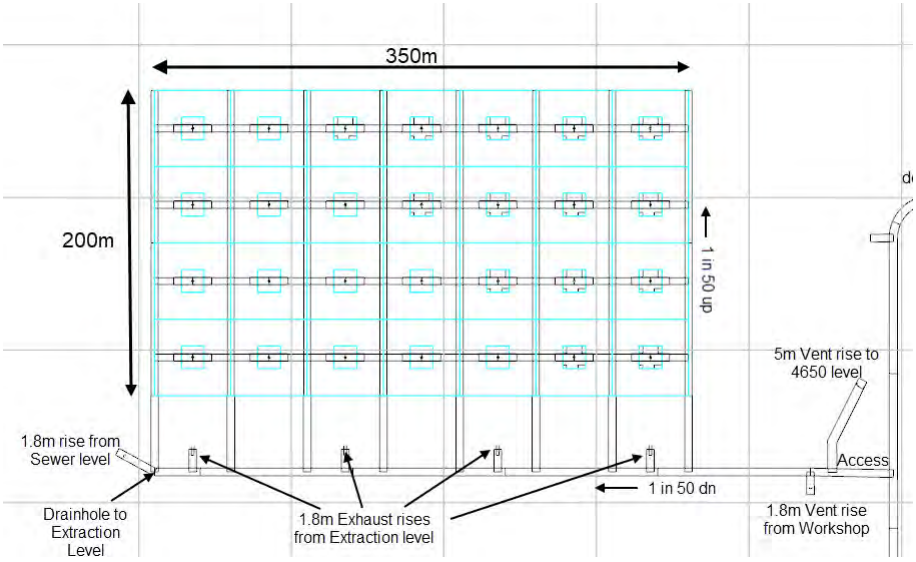


Figure 84: Undercut Level design for Cube Layout

Once the drilling of the drawbell from the Extraction Level is complete then the drawpoint brow area infrastructure is installed. This includes the installation of concrete roadways, cable bolts and a flow regulator to manage the drawpoint rill and which also serves to protect the rock brow of the drawpoint. The concrete floor utilises a blinding layer and then pre-cast concrete panels which are grouted in place to reduce the curing time required prior to operating heavy machinery in the drives. In poor ground conditions or in areas where large amounts of deformation are expected then steel sets are installed in the drawpoints to increase the level of ground support and reduce the amounts of future ground rehabilitation which will reduce the drawpoints availability during operation.

The initial drawbell section is drilled from the Extraction Level using upholes, as is the industry standard for Block Cave establishment. Prior to the blasting of the initial drawbell section a minimum 1m diameter raisebore hole is established in the centre of the drawbell to provide the initial void for the blasts. The upper section of the Cube drawbell is drilled out using downholes in multiple directions from the Undercut Level development to shape the drawbell. The Undercut Level configuration ensures that the full span across the top of the Cube drawbell is excavated without leaving any bridging pillars. The upper section of the drawbell is fired in 6 blasts to manage the void ratio of the blasts and access requirements on the undercut level to fire adjoining drawbells.

The production target for this footprint redesign is 100,000 tonnes per day. To achieve this rate, it has been estimated that two 63” Gyratory crushers are required, each with a design capacity of 50,000tpd. These crushers are located outside the influence of the abutment stresses created by the caving method. Prior to the commissioning of the first crusher the total material removal from the mine is capped at 100,000 tonnes per month, estimated on the assumption that until this point the Decline

trucking fleet is the rate limiting step. To utilise the various skills required to excavate and construct the primary crushers they are done in parallel with a 3-month offset. This construction approach has both crushers commissioned prior to the full capacity of a single crusher being reached enabling contingency in the system. The early commissioning of the second crusher also provides upside production capacity should the cave performance be above expectations.

To enhance the performance of the truck and loader fleet, the entire Extraction Level and truck routes to the crusher tip points will have engineered concrete roadways. These roadways will improve the operating conditions and reduce the wear on the equipment. Precast concrete panels with pavers will be utilised to minimize the installation time and maximise the life of the panels.

The primary ventilation direction will be against the direction of travel of the trucks within the footprint to improve visibility. There are raises from the edge of the Extraction Level footprint up to the Undercut level to remove the contaminated or return air and send it to the Primary Return circuit.

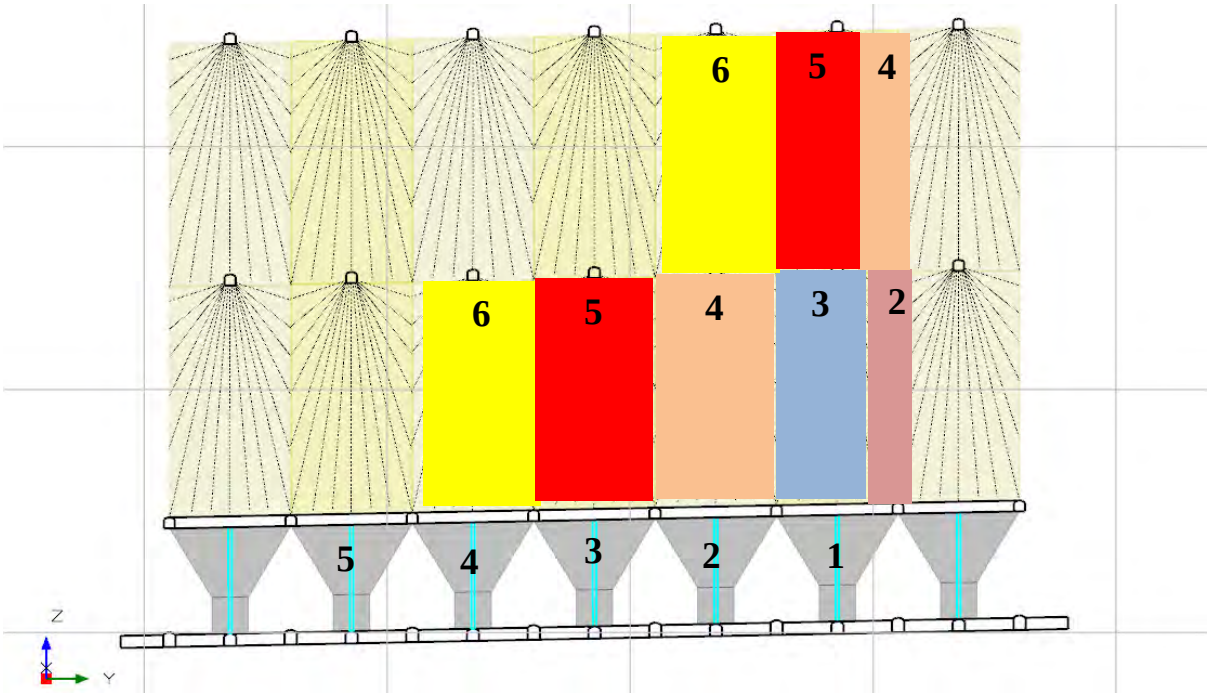
The gradients of the drives on the Extraction Level ensure that all of the water from the drawpoint sprays and from the cave column reports to the sumps on the entry side of the footprint. These sumps contain drain holes which channel the water to a lower “Sewer” Level where it is directed to the mine dewatering system and pumped to the surface. The first sump also includes an emergency vertical dam so that in the event of a large inundation of water to the footprint from a large rainfall event post cave breakthrough or the intersection of a significant aquifer during cave propagation, the excess water can be removed from the footprint without compromising key infrastructure. Production could continue during this period of inundation as the majority of the Extraction Level will still be accessible and operable.

The production rates from existing caves are limited by two key factors, cave establishment rate and fragmentation size. The cave establishment rate is determined by the undercutting and drawbell establishment rate and the draw rate from the established drawbells to enable cave propagation and manage the airblast and seismic risks. The fragmentation size is determined by the rock mass, any rock mass engineering such as hydrofracturing or blasting and how far the rocks have travelled prior to extraction from the drawpoints as there is a degree of secondary breakage as the rocks move through the cave column. Many caving operations, projects and studies currently underway utilise rock mass preconditioning by hydraulic fracturing to improve the caving rate by adding additional fractures into the rock mass which also influences the seismicity associated with caving, by dissipating stored energy through a greater number of smaller events rather than fewer but larger more damaging events, and the primary fragmentation. The influence of hydraulic fracturing on the rock mass is debatable as

the introduction of large fractures on a regular spacing reduces the magnitude of seismicity during caving which reduces the influence of these seismic events to fracture the rock mass as it caves. Also, the consistent fractures change the breakage planes of the natural rock mass which can result in long regular slabs.

The addition of 2 “post conditioning” levels from which 100m long blast holes are drilled generates effectively a substantial multi lift undercut 200m high. Over the area of the target production block this equates to a coarsely blasted volume of roughly 40 million tonnes. The aim of these levels is to improve the cave boundary definition, improve the production ramp up through the significant reduction of material in the first 200m of the cave column that is larger than $10m^3$, the maximum fragment size capable of being lifted by an LHD into the truck fleet. Analysis of secondary break curves has indicated that from above 200m the natural attrition occurring within the cave column as the rock fragments make their way to the drawpoints greatly reduces the number of rocks reporting at a size greater than $10m^3$ (Figure 86). As the productivity of the lowest/initial 200m or so of the cave column is crucial to the ramp up and financial performance of the cave footprint these 2 levels have been added to cost effectively manage any potential oversize material which will cause a production disruption. The firing of the post conditioning rings is linked to the establishment of the Cube drawbell directly below them (Figure 85) in the following sequence:

- a slot is established along the edge of the caving block using a 1.2m diameter raise drilled from the upper level to the Undercut level,
- Vertical blast holes are drilled along the slot drive and fired in a retreating sequence to open up a void along the edge of the target ore block. The fired slot will also act as a destressing area and redirect the natural ground stresses around the working areas protecting the operational areas.
- Once the slot is open along the length of the first Cube Caving drawbell, and the majority of the undercut material has been drawn and a suitable void is available the front 15m of the blast holes over the first Cube Caving drawbell on the bottom level are fired to full height into the slot void and the drawbell void below.
- The remaining 35m is fired once 80% of the front 15m has been extracted creating a suitable amount of void to accommodate the blast.
- The post condition blasting associated with the subsequent rows are all fired to the full height and area of the drawbell once sufficient void has been created.
- The upper level is also initiated with a slot to ensure the rings have void in front of them to full height. Once the slot has been fired and the material has been cleared from below to create sufficient void then the complete area above the drawbell is fired to full height. These levels are essentially mined as large stopes.



- *Figure 85: Long section showing establishment sequence of the drawbell, undercut and the two Post blasting levels*

The above firing sequence has been established to reduce the oversize material in the lower 200m of the ore column, define the edges of the caving block and to enable a faster production ramp up and therefore improve the project economics. The impact of the large blasts on the release of seismic energy and the changes in stress as they move across and above the footprint area have not been assessed, beyond identifying that they move the seismic events well above the primary working levels, Extraction and Undercut levels, in the areas that have been blasted. The stress change in the abutment zone where the next post conditioning blast needs to occur has not been assessed.

The risk of airblast associated with the post conditioning blasts has been assessed as minimal as the amount of material extracted from the blasts is only sufficient to enable the subsequent blast in the sequence to have a satisfactory amount of void, noting that the blast sizes can be adjusted to manage any perceived risk and that these post conditioning levels are included only as an opportunity and are not pivotal to the Cube concept.

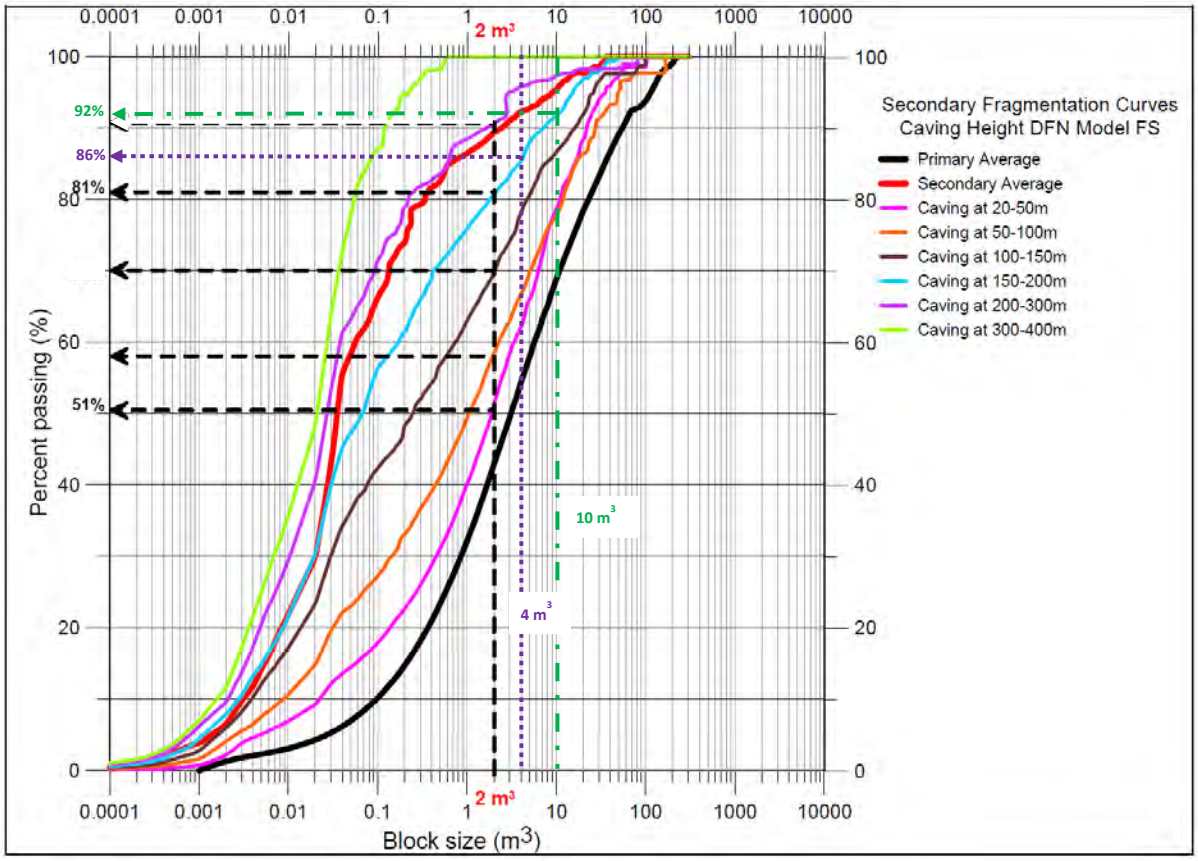


Figure 86: Secondary Fragmentation Curves by height for Cadia East PC1 (Internal Document)

The segregation of cave establishment tasks across multiple levels and areas allows for the scheduling of tasks in parallel rather than in series. This significantly increases the level of flexibility within the schedule and also reduces the overall time required to establish the caving footprint and associated infrastructure to support nameplate production. It is estimated that the time to develop the Extraction and Undercut Levels can be materially reduced and that the drill and blast time for the drawbells to establish the production system are dramatically reduced compared to the existing El Teniente layout.

Opportunity

There is an opportunity to increase the Extraction Level pillar size further by deferring the mining of the longitudinal link drives between the drawbells until after the undercut has been fired over them. There is a further opportunity by not mining every second Extraction Drive until the undercut has passed over, resulting in the majority of pillars on the Extraction Level having plan dimensions of greater than 40m x 40m. Neither of these scheduling delays to the long-term excavations impacts the ability to remove the requisite swell material from the drawbells during the establishment phase as each drawbell can be accessed through at least two drawpoint drives.

7.1.2 Development Approach

The preferred development approach for the Extraction and Undercut Levels is;

- maximise the amount of straight-line development whilst minimizing the number of heading size and shape changes and limiting the number of gradient changes across the footprint,
- limit the number of intersections, as they require additional ground support and incur slow rates of advance,
- increase the angle at any required intersection to as close to 90 degrees as possible for stability, noting that for efficient long-term production loading nearly all existing layouts utilise a drawpoint turn out angle of between 50 and 60 degrees resulting in slender pillars which are susceptible to failure leading to larger intersection spans and smaller pillar cores,
- where possible enable the mining direction of any heading to be uphill to allow gravity to drain any water from the face,
- provide an adequate number of independent headings to enable high performance development rates through the use of parallel development of headings,
- design the level to minimize the interactions between the various activates required to establish it.

The Extraction Drives will be mined at a consistent height of ~6.5m to provide sufficient height for the loading of the truck fleet by the largest of the identified loaders to be used within the footprint, the Sandvik LH621i. The consistent drive height will improve the efficiency of development and improves the stability of the drive backs by not having variability in the drive sections that don't necessarily have to be at 6.5m high. If a variable back profile was utilised there would be approximately 10m of development between the intersections at 5m high and another 10m that was stripped to gain the 6.5m height in intersection for loading.

All drawpoint drive development will be mined at 5m x 5m to enable efficient boring and ground support installation during establishment. The final profile allows for effective operation of a 21t loader or a larger capacity continuous loading unit. The edges of drives along the tramming route of the loading units will be chamfered for high performance operation and minimisation of damage to the machines. These chamfers have a negligible impact on the stability of the intersections and the overall level.

With the straight and consistent profiles of the Extraction and Undercut Levels they are well designed to be excavated using long round jumbos in the typical drill and blast approach or mechanical cutting units in the future when that technology advances sufficiently to be used in the specific ground

conditions of the relevant mines.

7.1.3 Undercutting Strategy

The undercutting strategy for the new design is a conventional or post undercut sequence. This involves the blasting of a small drawbell from the Extraction Level which defines the drawpoint brows and then the blasting of the upper parts of the ultimate drawbell shape from the Undercut Level which completes the continuous dislocation of the targeted ore block from the Extraction Level workings. This methodology allows for the confirmation of full blasting success of the lower drawbell component before completing the larger blasts from the Undercut Level. The firing sequences ensure that there is sufficient void to accommodate the swell of material from the next blast and also ensures that all blasted material is removed on the Extraction Level which is the one set up for optimum materials handling, rather than needing to remove material from the Undercut Level as is the current industry practice when utilising an Advanced or Pre undercutting strategy. The undercut firings will be fired in multiple steps to manage the energy release associated with establishing them. The proposed methodology can use either electronic or wireless detonators to manage the explosive energy release. The sequence of firings also considers the separation pillar between the void being created in the drawbell and the Undercut Level development to minimize the chance of damage to the Undercut Level.

The design of the Cube undercut has been integrated into the drawbell design to ensure the combined excavation efficiently and effectively channels the broken rock in the cave column to the drawpoints whilst also shaping the Major and Minor pillars for maximum stability.

Due to the size of the ultimate drawbell being 50m by 50m on the Undercut Level even when breaking the blasting sequence into manageable portions the final blast is still greater than 1,100m^2 which is 70% larger than the full area of a 32 x 20m El Teniente drawbell undercut firing. This large undercutting advance in a single step will likely result in a stand-off period to allow the rock to resettle after the blast. During real world implementation of the design the size of the undercut firings may be reduced to align with the localized ground conditions at the mine.

Some of the existing Block Cave Projects which utilise a Post Undercutting sequence are increasing the effective undercut blasting area by including rings of ~40m long upholes every couple of standard undercut rings to fracture the rockmass immediately above the drawbell in the aseismic area (Figure 87). This approach is only effective in a post undercutting sequence as an Advanced undercutting sequence does not have sufficient void for both the main undercut material and the fracturing holes to break and mobilise the rockmass, rather the fracturing holes may just add some additional cracks

in the trough area of the undercut.

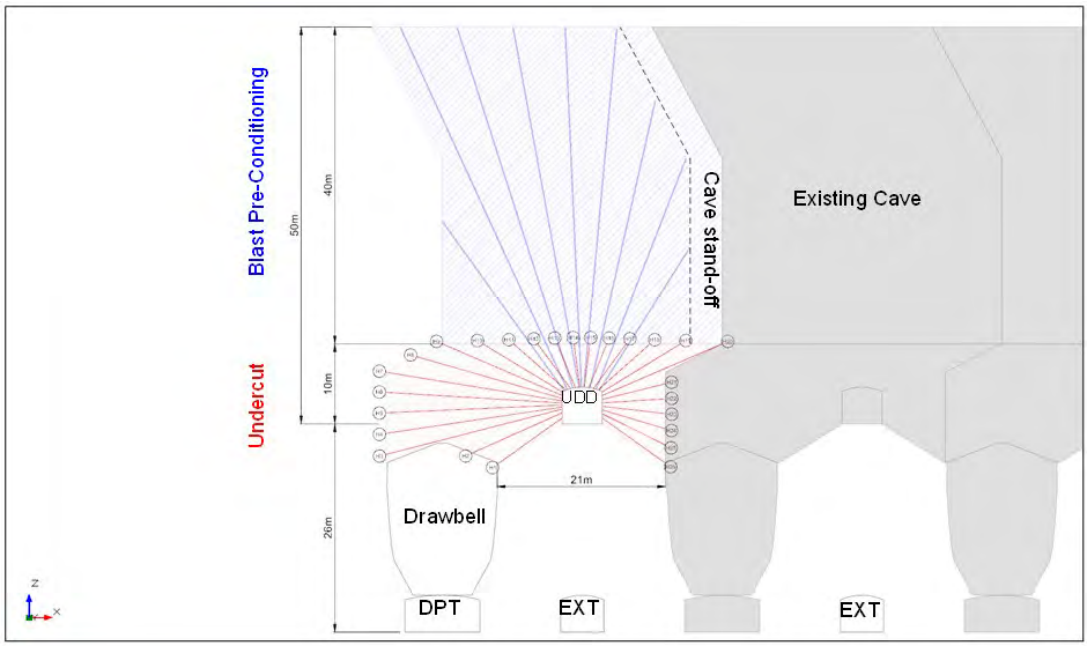


Figure 87: Post Undercut geometry with Blast Pre-Conditioning (Newmont)

7.2 Cave Propagation Management

As the initial cave propagation is vital to the successful definition of the target ore block that will be mined over the life of the Extraction Level, two additional Post-Conditioning levels (Figure 88) have been included as an additional option in the design. These levels will provide numerous advantages including:

- Definition of the lower 200m of the ore block by targeted drill and blast directly above the newly established drawbells,
- Removal of seismic activity from the vicinity of where the majority of personnel are working during the cave establishment phase, i.e. the Extraction and Undercut Levels,
- Ensuring that >99% of the rock fragments generated in the lower 100m, >96% of the rock fragments in the 100 to 200m zone, are less than 3m in maximum length or $10m^3$ in volume and therefore manageable through the Extraction Level materials handling system without causing interruption. Of the 1 to 4% estimated to be greater than $10m^3$, there will be the opportunity for them to be reduced in size as they travel up to 200m in the draw column before reporting to the drawpoint ,
- Providing ~40Mt of blasted material above the top of the drawbell which can be drawn at an increased rate to improve the financial return of the project,
- The location of the potential air gap that is created between the broken ore column and the cave back is relocated to >200m from the Extraction Level thus eliminating the exposure of personnel to this potentially catastrophic caving risk. The increased separation also enables a larger void to be developed in the early stages of natural caving without impacting the safety or production of the Extraction Level.

The staged post-condition blasting will use the void created through the establishment of a slot on the longitudinal edge of the mining block and the full drawbell to blast into in a similar manner to large scale open stoping operations, such as Mount Isa and Olympic Dam in Australia. The post-conditioning blasts are therefore unconfined and can use the void in front of them to enhance the refractory breakage of the rock mass by the initiated explosives and the material reports to the drawbell below. The blasts can also include a larger number of holes on a longer delay period than the confined pre-conditioning blasting conducted at Cadia East and El Teniente operations thus reducing the amount of explosive initiated on a given delay and reducing the shock impact and seismic response to the blast. The post-condition blasting rings will be drilled in parallel rings with a ring pattern designed to cover the 50m x 50m x 100m high block of ore above a specific drawbell. A slot is established and then the full rings are fired into it. For the first section of rings associated with the front row of drawbells the first 15m is initially fired into the slot void, then the remaining 35m is fired

once enough material has been removed to generate the required swell void. The full lateral 50m is fired for the remaining drawbells. The full upper 100m section is fired in a single lift due to the void available to accommodate the blasted material. The sequence of blasts is shown in Figure 85. All of the rings associated with a given drawbell are fired in a single blast with the individual blast holes having separate timing delays to minimize the vibration impacts on the rockmass.

The 200m directly above the Undercut Level has been identified as the key zone for post-conditioning as this is the area of the ore block which encompasses the initiation of natural caving as the mining area is undercut. This initiation phase and the following aseismic phase, the period directly before the critical hydraulic radius is reached and natural caving commences, where there is little to no seismic energy released as the caveback yields, generates large fragments as the caveback starts to fail/unravel. With the limited draw column heights at this stage of the cave there is limited opportunity for the mechanisms within the cave columns to reduce the size of the fragments before they reach the drawbells which can then lead to considerable production interruptions and possible Extraction Level pillar damage due to stress build up within the cave.

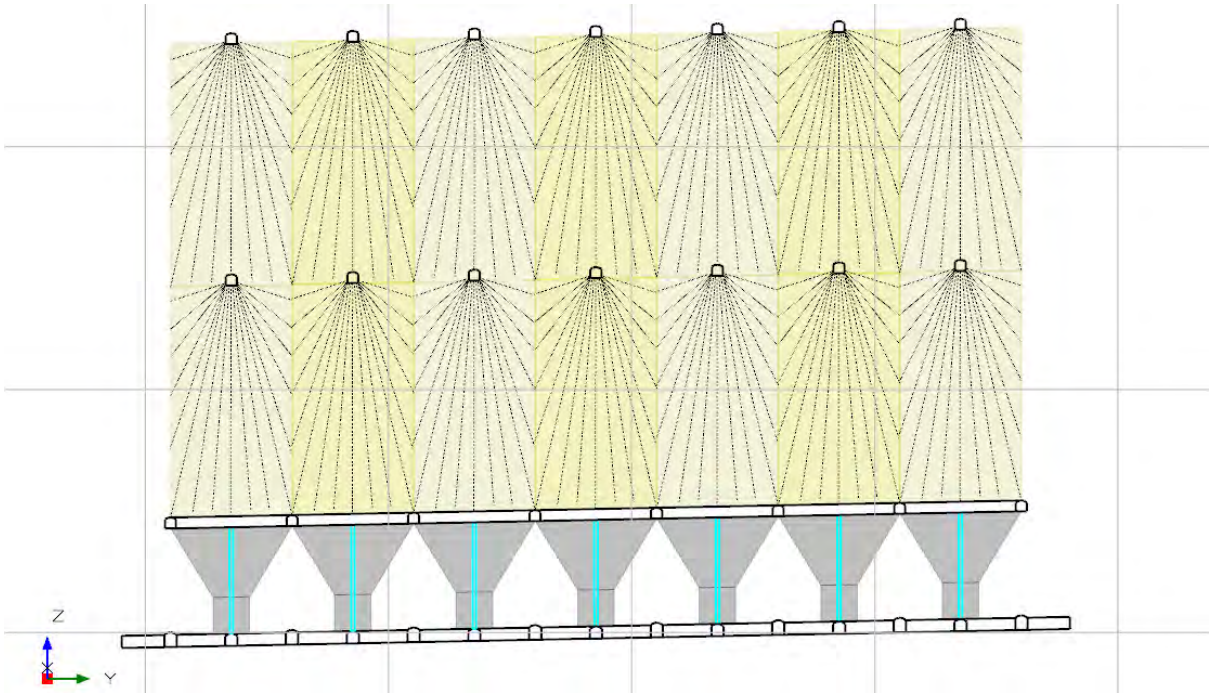


Figure 88: Long section showing drawbell, undercut and the two Post blasting levels

The two post condition blasting levels are independent of the Cube layout and are included as an enhancement to the ramp up and early-stage operation of the caving footprint. This configuration could be included, in a modified form, to the existing El Teniente layouts to deliver the ramp up and reduction in oversize benefits identified in this research. The estimated cost associated with the post conditioning program is roughly $0.95/t which includes the development of the levels and the drill

and blast costs. Whilst this is a higher unit cost than just treating the oversize in the drawpoint, the in-drawpoint treatment costs do not consider the production and flow interruptions caused by the oversize material and the safety impacts of having additional personnel and machinery in the production area.

7.3 Operating Logic

Through the Cube redesign, the large pillars established on the Extraction Level enable the use of larger tunnel sizes without compromising the long-term stability of the level. The Extraction Drives can also be mined at 6.5m high, to facilitate the loading of trucks, without compromising the level's stability as the height of the tunnel has a lesser impact on the integrity of the pillars than the horizontal width depending on the stress regime.

The outcome of redefining the materials handling system on the Extraction Level is that the productivity of the Extraction Level can be significantly improved by removing the tramming distance constraint of the LHD and also by reducing the number of production interruption events by increasing the size of an "oversize" fragment.

The largest fragment that can be accommodated varies at each part of the process. The physical design, the drawbells and drawpoints can accommodate a fragment ~20m^3. For the mobile equipment, LHD and trucks, it is ~10m^3 i.e. the largest that the LHD can fit in its bucket and for the crusher it is ~4m^3. By increasing the size of the largest fragment that causes a production interruption, i.e. that passing through to the muckpile or that which requires a secondary treatment prior to entering the materials handling system, the number of production disruptions is materially reduced, resulting in more drawpoints being available for production loading. This also increases the productive time of the loading units as there is less time spent relocating oversize material from the producing drawpoint so that production can continue, or in undertaking clean-up activities at the ore pass grizzly. Additionally, the Cube layout enables approximately 50% of the truck loading points to have the trucks loaded from both sides thus reducing the loading time and improving the truck productivity. As the trucks all travel in a consistent loop there is no interference as more units are added, resulting in no productivity difference between any of the drawpoints on the level, the only variable is how many trucks are added into the system based on the hauling distance.

As identified in the design chapter, the estimate of rock fragments greater than 4m^3 is mostly in the initial 200m of the natural cave column (approximately 86% passing 4m^3), see Figure 89. This is due to the limited seismicity, aseismic, in the early stages of the cave propagation so the rock fragments are mostly formed by the spacing between the natural fractures in the rock mass as the caving span opens up and gravity induces rock fall off. Once the fragments have travelled through approximately 200m of caved material, the number of large (greater than 10m^3) fragments presenting at the drawpoints is almost eliminated (less than 2% of rocks at the drawpoint are estimated to be >10m^3) as they have either broken up during their downward journey (through attrition on their edges or point

loading along their length (Pierce 2010)) or they are passed by other smaller fragments which move faster through the cave column ((Power 2004), (Sharrock and Hashim 2009), etc.). It is with this observational and empirical support that the lower 200m of the cave column has been targeted for additional blasting post the establishment of the drawbell to remove the potential production interruption rocks before they present at the footprint. By treating the rocks in the cave column, it is more cost effective and has less impact on production, as the cave column blasting is done in parallel with recovering rocks from the drawpoint rather than halting production from a drawpoint when a large fragment presents itself. When the large fragments do present, they are of such a size that drilling and blasting, with explosive or non-explosive, methods will be the most effective thus simplifying the secondary fleet requirements. Existing operations utilise a range of secondary break equipment, including mobile rock breakers, small and mid-size drilling machines, at the drawpoint due to the large variety of rocks which require treatment.

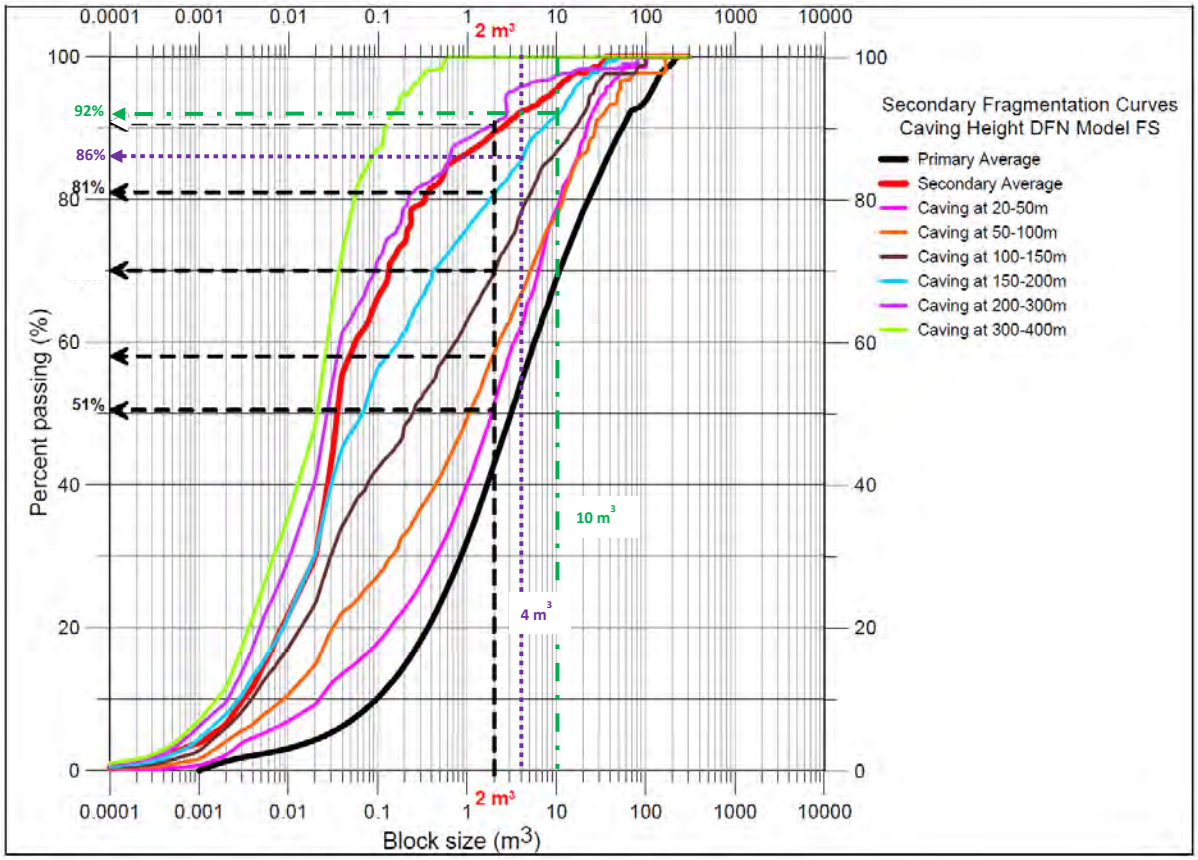


Figure 89: Fragmentation Curves by height for Cadia East PC1 (Internal Document)

The volume of material blasted above the top of the final drawbell shape is approximately 40M tonnes, which provides enough blasted material to support an accelerated ramp up of production compared to the existing caving projects which are under tight draw control conditions in the initial establishment years to ensure the production draw matches the caving rate and that there is no potentially damaging airgap being formed. With the first few years of production being crucial to the financial success of

the mine, having a large volume of this material as blasted and available is very financially beneficial. With the natural caving commencing some 250m above the Extraction Level there is a reduced risk of airblast affecting the Extraction Level as the caving muckpile is monitored to ensure there is only sufficient void available prior to the next post conditioning blast. Should natural caving commence in this area before the blast rings can be fired then the drill holes potentially act as points of weakness to assist caving and the caved material is removed from the Extraction Level under strict draw control conditions as per the existing approach.

Most large-scale caving projects estimate a combined production of between 10 and 15M tonnes in the first 3 years of caving. The estimates for the Cube cave are conservative at around 23M tonnes or from a first principles basis at greater than 57M tonnes. If it is assumed that a tonne of cave material has a value of $100/t (Net Smelter Return (NSR)) then this equates to an increase in revenue in the first 3 years of between $1.3 and $4.2 billion. If this assessment is extended to cover the first 5 years of production, then the existing range is between 40 and 80M tonnes for the El Teniente layouts and 85 to 129Mt for the Cube resulting in a financial improvement of approximately $4.5 to $4.9 billion.

The productivity of the footprint is no longer constrained by the size and tramming length of the LHD as the LHD now only loads the rock from the drawpoints before traveling a short distance to load the truck at an intersection in the Extraction Level. The trucks travel in a consistent direction through the Extraction Level, operating in expanding parallel loops, before then tipping directly to a crushing unit, located in a stable area off the footprint.

An assessment of the footprint productivity was completed utilising the ORB simulation package from Polymathian, Figure 90, which confirmed the operating logic and performance expectations of the Cube layout. The Polymathian simulation models have been calibrated using numerous caving operations including Cadia East (Donaldson 2021), NorthParkes and Freeport where their optimisation program ORB is utilised for dispatching the production loaders. Due to the high number of drawpoints available for each LHD it was assumed that should a hangup occur the loader would just relocate to it’s alternate drawpoint and continue producing and there would therefore be no impact from oversize material.

Figure 91 shows the simulation input assumptions. The production target for the nominal 350m x 200m footprint was 100,000 tonnes per day and this was achieved with 7 x 21t loaders working with 13 x 65t diesel trucks, as shown in Table 4. It can be seen from the simulation results that there is a diminishing return in adding more trucks to the system as they begin to queue at the loading points with 7 loaders operating, Figure 92. 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 MHS as the 2 crushers were selected to achieve 100,000tpd so if >120,000tpd was required additional crushing and conveying capacity would be required.

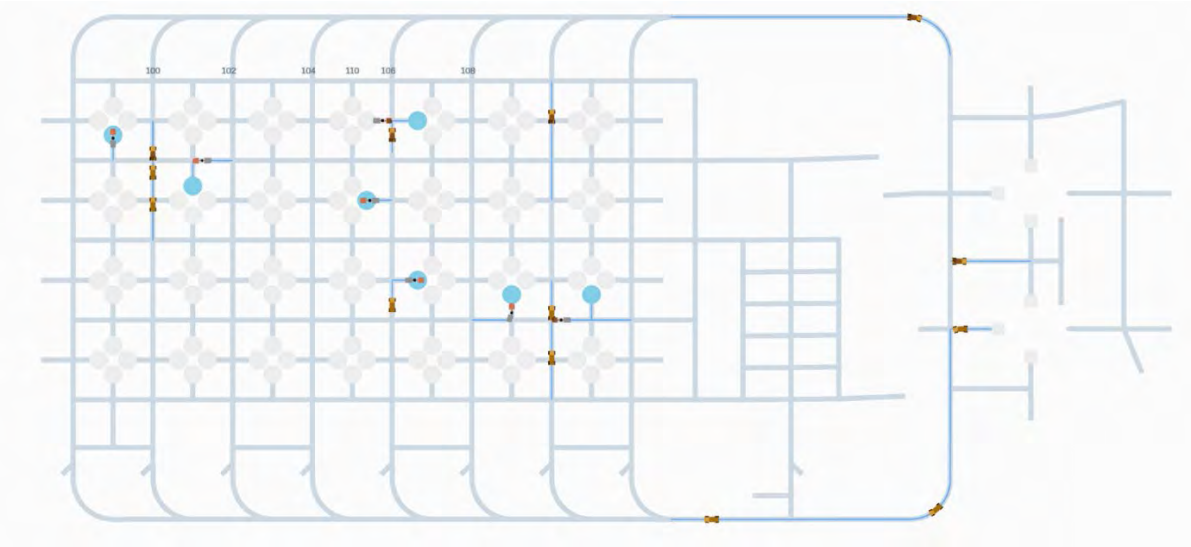


Figure 90: Screenshot of production simulation

LHD Model Inputs

Metrics	Value	Units
Type	Diesel	-
Number	7	#
Loader Bucket Size	21	t
Bucket Factor	95 +/- 10	%
Bucket Load Duration	45	sec
Bucket Discharge Duration	7.5	sec
LHD Length & Clearance	12.5 (20.0M INCL. CLEARANCE)	m
Avg. Max Speed (Loaded, Empty)	6.00	m/s
Acceleration	0.40	m/s^2
Deceleration	0.60	m/s^2
Operational Days	365	days
Operational Hours	22	hours

Truck Model Inputs

Metrics	Value	Units
Truck Capacity*	63	t
Discharge Duration	16	sec
Avg. Max Speed	6.00	m/s
Acceleration	0.40	m/s^2
Deceleration	0.60	m/s^2
Operational Days	365	days
Operational Hours	22	hours

Figure 91: Simulation Input Assumptions

Table 4: Cube 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

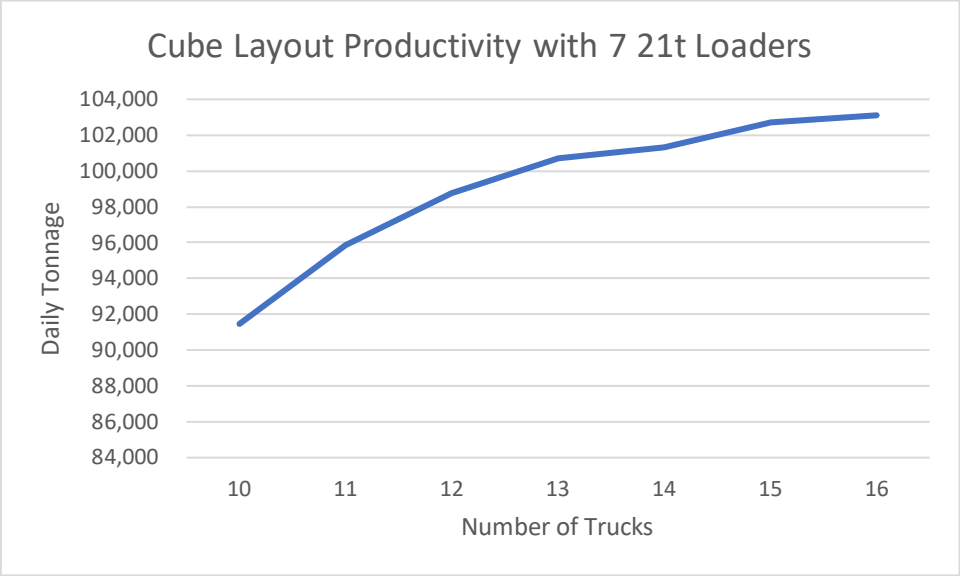


Figure 92: Cube Layout productivity assessment with 7 21t loaders

The layout allows for the loader or secondary break units to fit entirely within the drawpoint drive and allow any other vehicles operating in the area to pass by. The loaders operate within a specific area from the drawpoint to the truck loading point which is a maximum of 50m from the drawpoint. There is always an alternative truck loading point should the primary location be unavailable due to breakdown or rehabilitation activities. This reduced operating distance for the loader increases their efficiency and reduces the operating costs accordingly as there is limited tramming related wear on the units, i.e. centre hitches, tyres and transmissions. The high number of drawpoints available per loader results in a level of redundancy that ensures there is always a drawpoint available for the loader to operate in.

With the removal of high-speed loader tramming there are considerable safety benefits in the operation of the Extraction Level, including high speed vehicle interactions, sudden stopping of loaders resulting in the loader operator being thrown around the cab, hot tyres and engine fires. In the nominal footprint layout devised for this research, only 3 to 4 of the Extraction Drives are required to meet the production requirements, leaving the other 4 to 5 Extraction Drives open for other supporting tasks such as services repairs, rehabilitation and drawpoint sampling which significantly limits the

interaction with or influence of production equipment on these activities within the operating footprint. To enhance the ore recovery from the level additional Extraction Drives might be used to spread the draw of material across the level and reduce overdrawing from a few drawpoints, particularly transitioning between active Extraction Drives on Day and Nightshifts. The opportunity therefore exists for the production rate from the layout to significantly exceed the targeted 100,000tpd providing it with catchup capacity during operations or the opportunity for the mine to increase the production expectations should other materials handling system constraints allow it.

7.3.1 Equipment Operating Parameters

The one direction haulage loop through the Extraction Level and out to the Crusher tipple area limits the amount of congestion within the haulage circuit. Each of the trucks can be redirected to a different haulage location once it has dumped its load and similarly can be redirected to a different crusher dumping location as it is transiting to the crusher area. This flexibility ensures that any interruptions at loading or tipping locations do not directly relate to lost productivity as the truck units can be reassigned to keep the production flowing.

The loading units and trucking units will be matched to ensure that each truck is loaded in three (3) passes by the loaders. This matching of equipment limits the operational losses associated with partial truck loading or requiring a short load from the loaders to fill the trucks. Initial operational concepts included the use of smaller hauler units, similar to the Volvo HX automated hauler, that matched a single loader bucket but these concepts were discarded due to the number of hauler units required and the associated congestion around the crusher tipping points.

The main Extraction Drives have been designed to allow loading of the trucks from both sides at each intersection, this is to not only improve the truck loading efficiency but also to provide additional flexibility for the loaders by ensuring that there is a backup loading and tipping location for all drawpoints. For the parallel drawpoints the backup loading location is the one directly opposite the primary one. For the perpendicular to the Extraction Drive drawpoints the backup loading drawpoint is either the one directly opposite the primary one or one of the two from the spare drawbell in the Extraction Drive, based on the proposed layout having 4 drawbells across the footprint and 3 loaders working in the one Extraction Drive.

There are slightly varying loading times from the parallel or perpendicular drawpoints, relative to the Extraction Drive. These differences are more to do with the positioning of the trucks than the LHD routes. In the perpendicular drawpoints (Figure 93), the most efficient truck loading scenario is to

assign 3 loaders in the Extraction Drive and have the truck progress forward through the Extraction Drive to be loaded by each loader rather than shuffling backwards and forwards to allow a single loader access to its loading point. This strategy also enables additional trucks to operate in the same Extraction Drive without excessive queuing delays.

The parallel drawpoints (Figure 94) are more efficient for the trucks as they can park in the one location and be loaded from both sides. This strategy also allows the loaders to have access to two loading points on each side of the truck loading area.

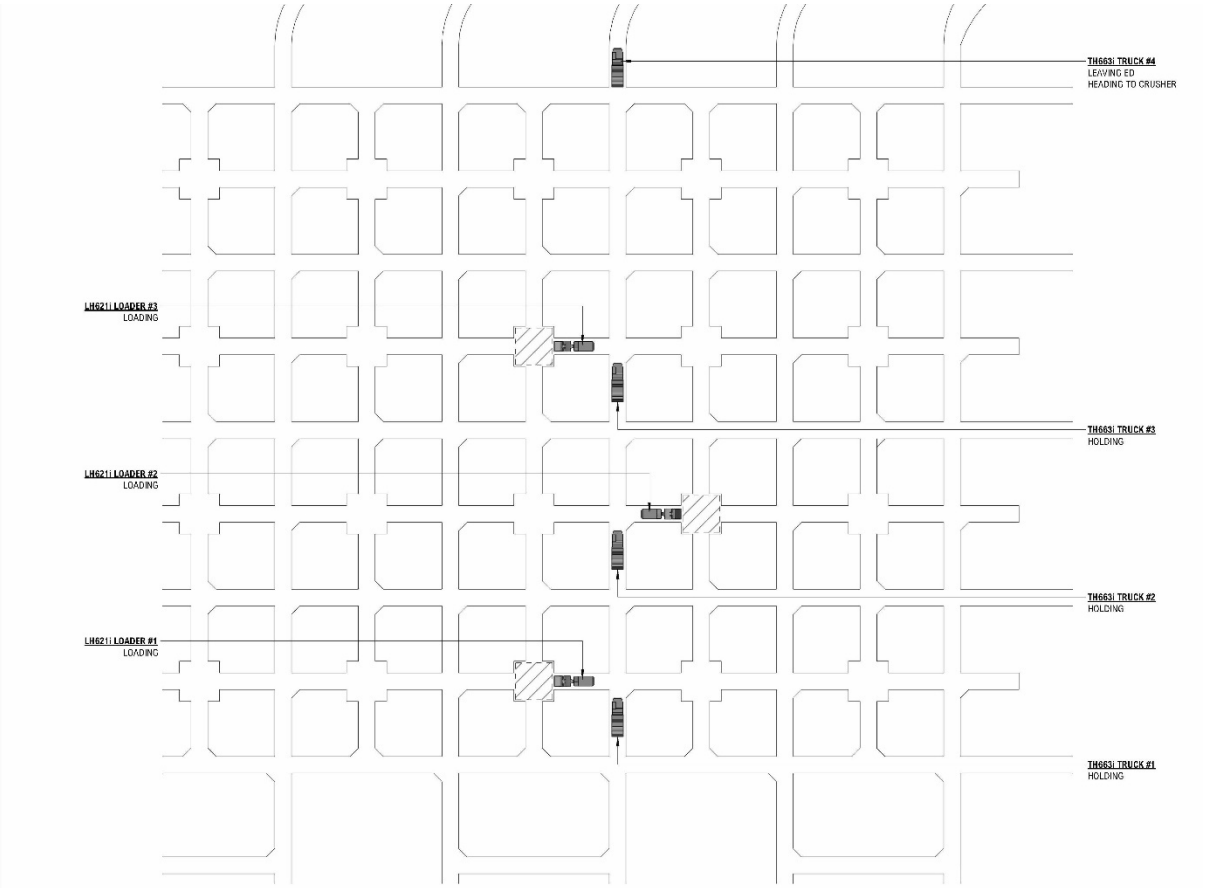
With the high levels of truck and loader interactions there is the opportunity for enhanced safety in the Extraction Level through the use of collision avoidance technology.

The new layout and mobile fleet operating strategy ensures that every drawpoint has essentially the same instantaneous production unlike the existing El Teniente layout which sees drawpoint production variability due to the length of the loader tramming distance. Comparison production scenarios were completed comparing the various El Teniente loader tramming scenarios and the new Cube design (Table 5) on a 350m long by 200m wide footprint.

Table 5: Extraction Level Production Rate Comparison

Layout	Examples	Production Technical Limit (22h/day)	Production Likely Upper Limit (22h/d)	LHD Size	Estimated Operating Cost ($/t)
32 x 20m El Teniente LHD -> Dual side Crushers	Cadia East*, Red Chris*, Northparkes*	110,000tpd (16 LHD)	70,000tpd	21t	3.10
32 x 20m El Teniente LHD -> Central Ore Passes	El Teniente, DMLZ	104,000tpd (12 LHD)	75,000tpd	14t	5.90
32 x 20m El Teniente LHD -> External Ore Passes	Oyu Tolgoi, Cascabel	107,000tpd (10 LHD)	70,000tpd	14t	5.95
50 x 50 Cube LHD -> Truck	This PhD research	180,000tpd (8 LHD & 20 Trucks)	105,000tpd	21t	3.01

Note: The Operating costs include all costs to get the material from the drawpoint to the Crusher



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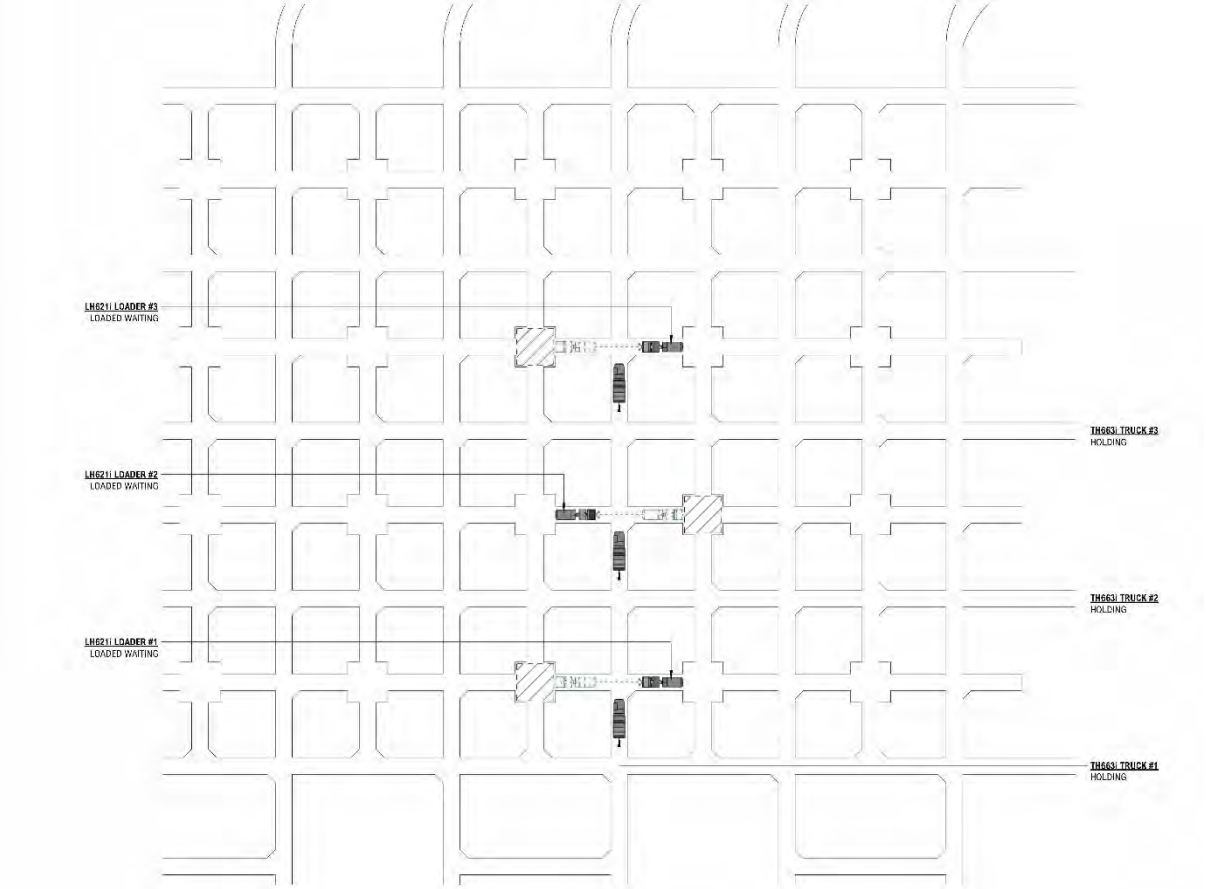

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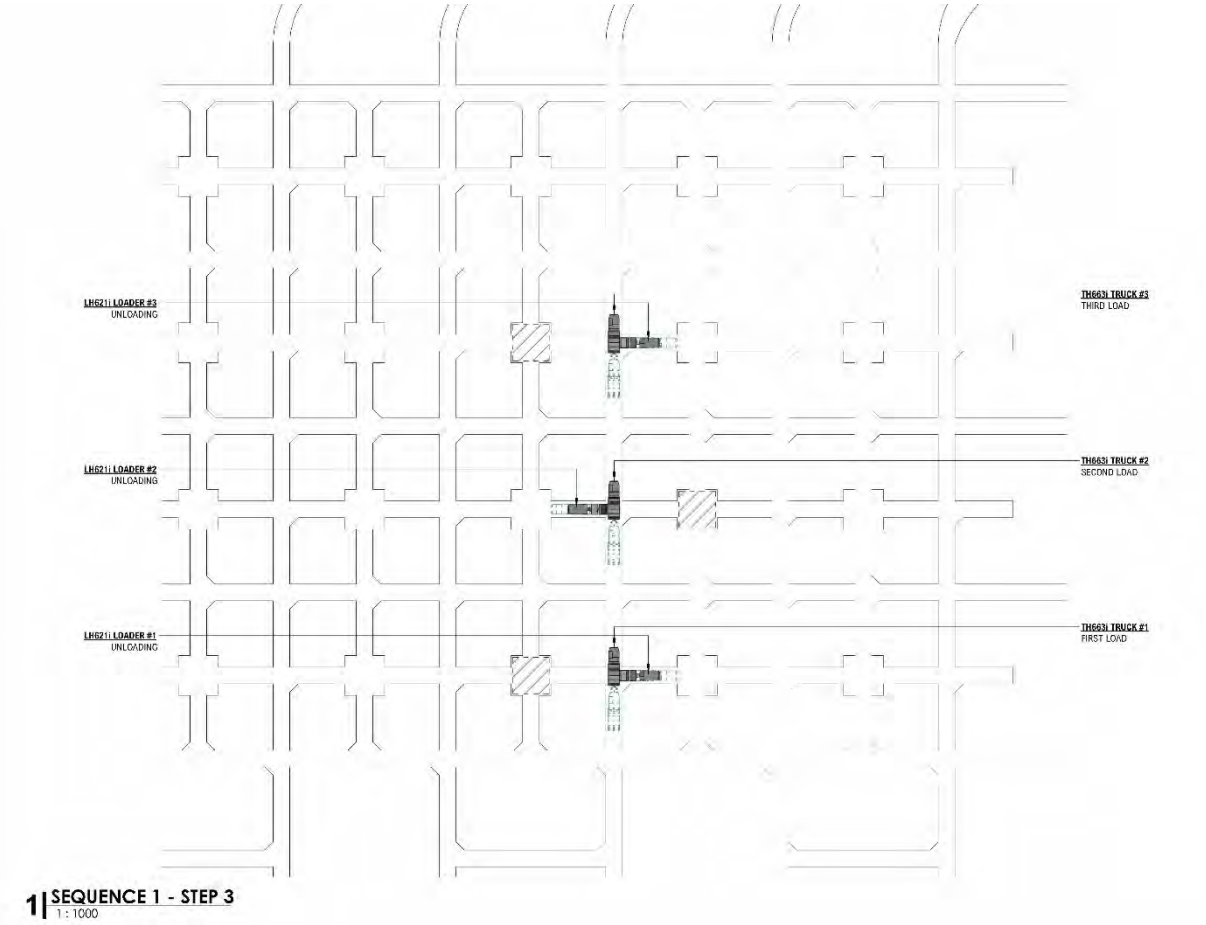

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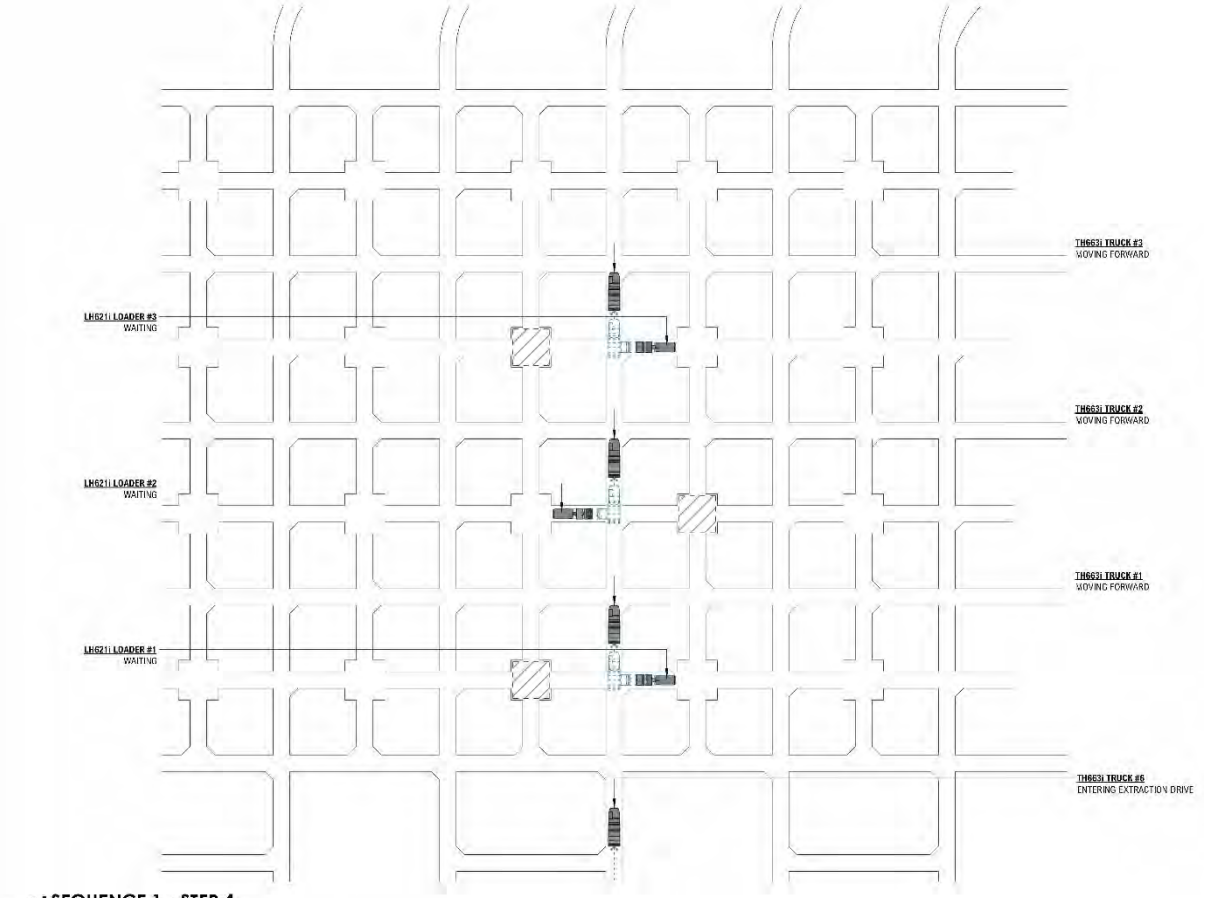

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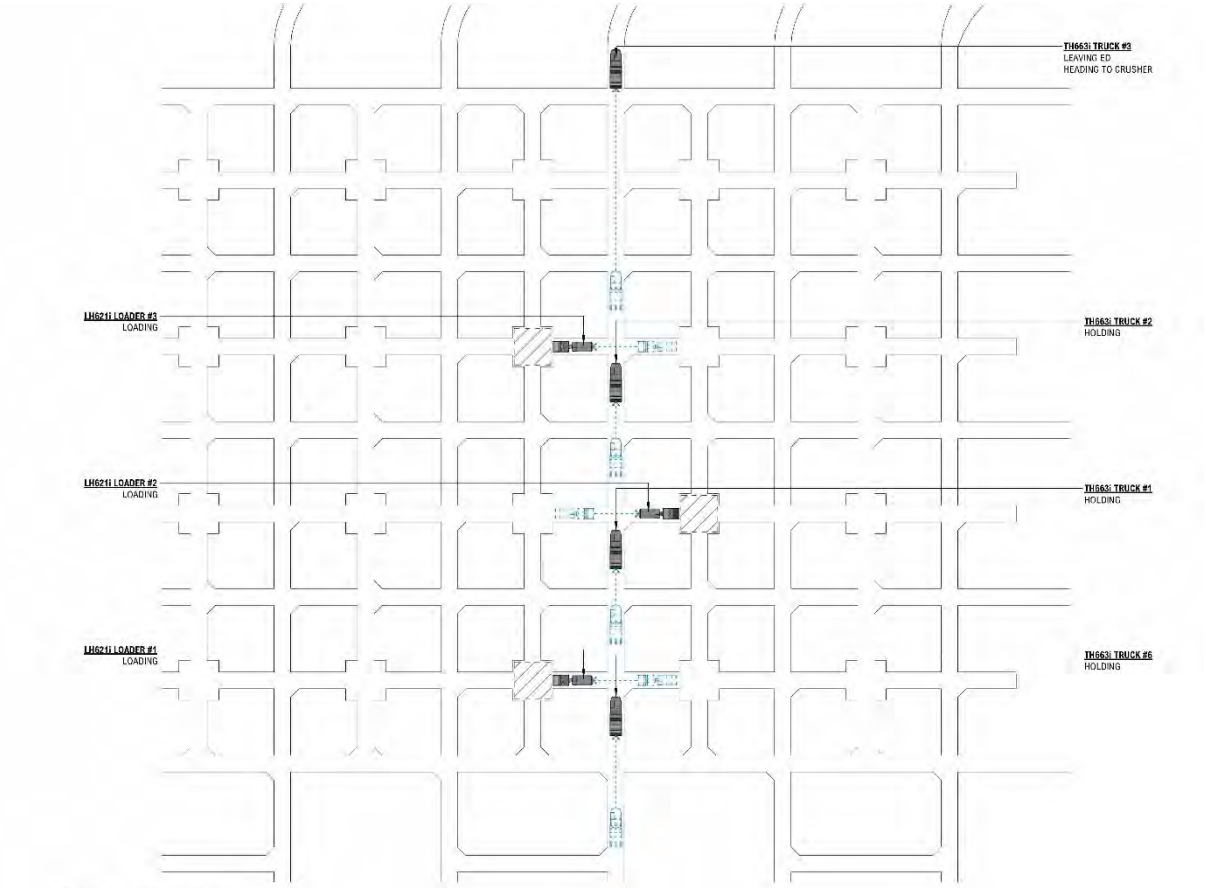

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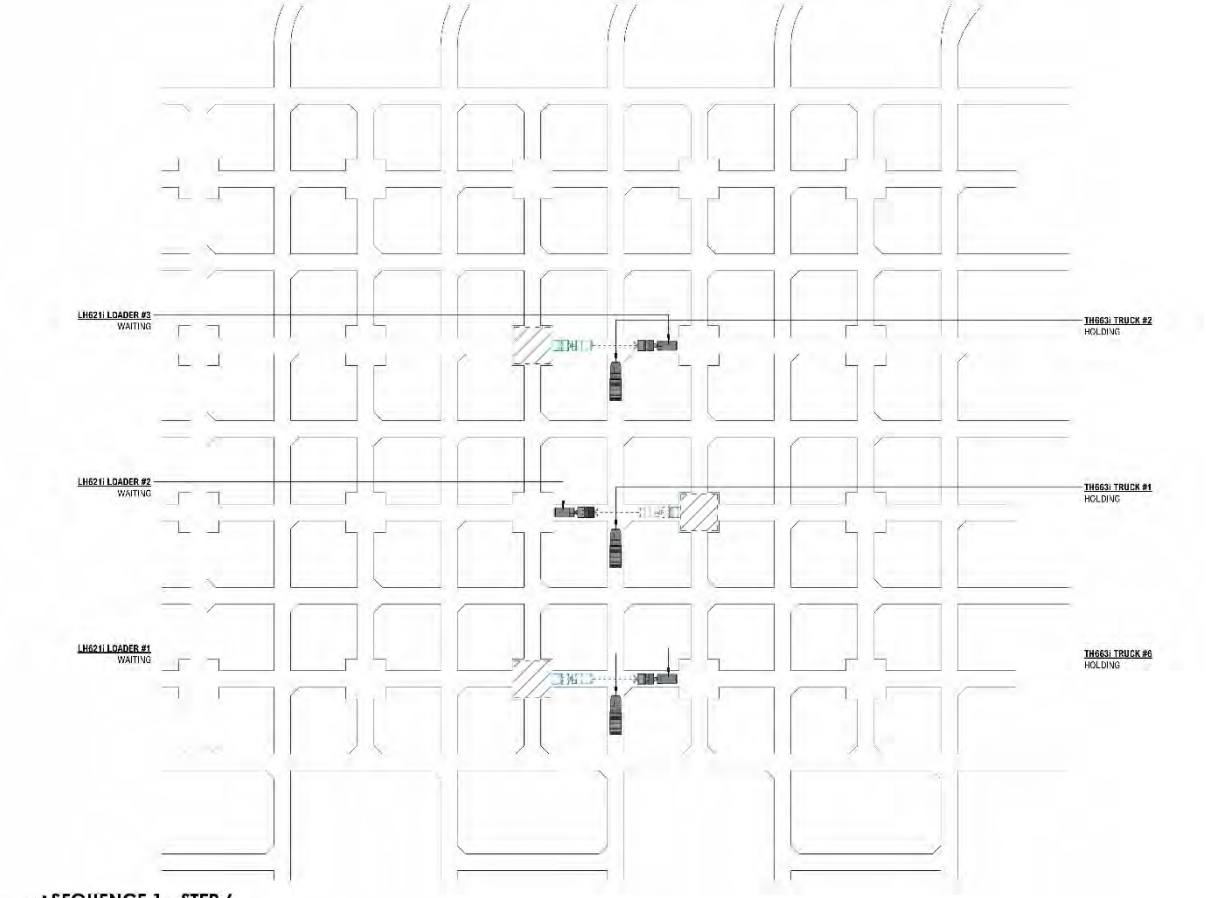

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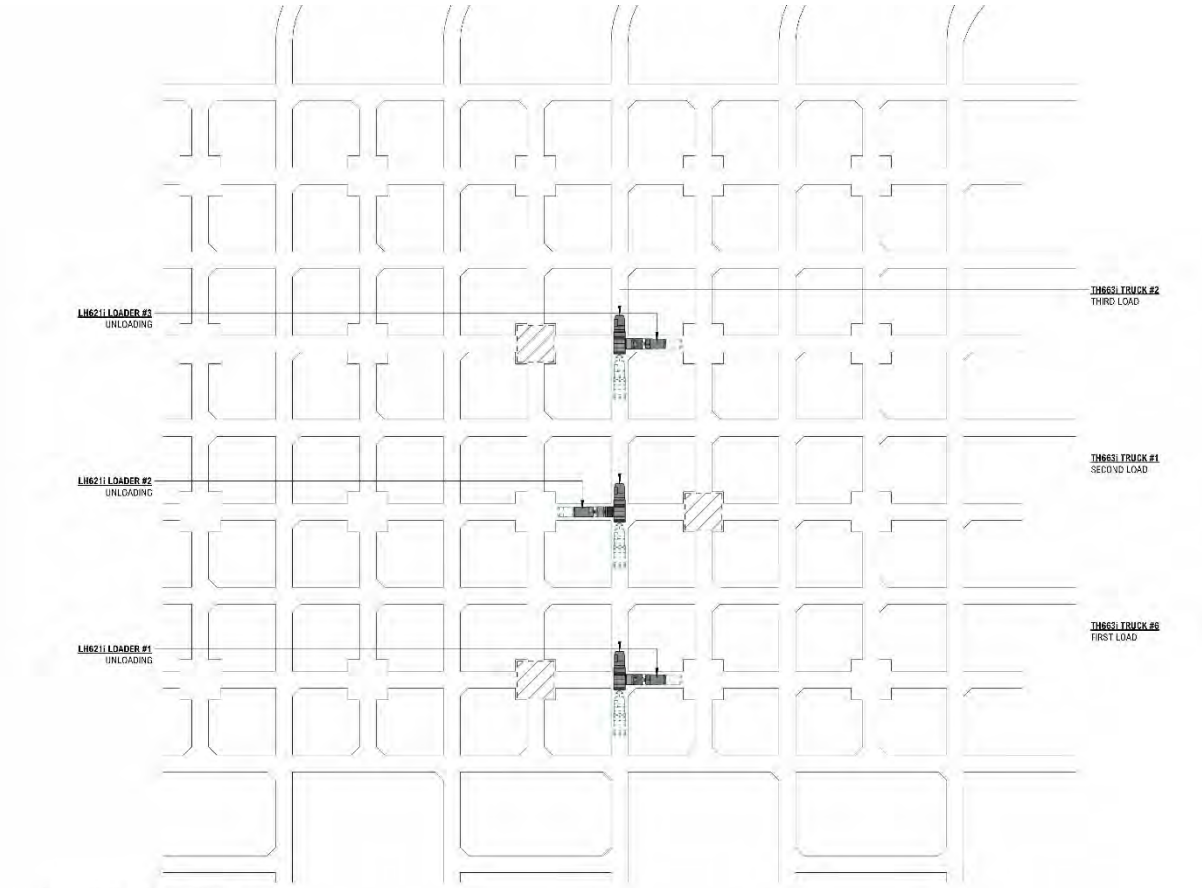

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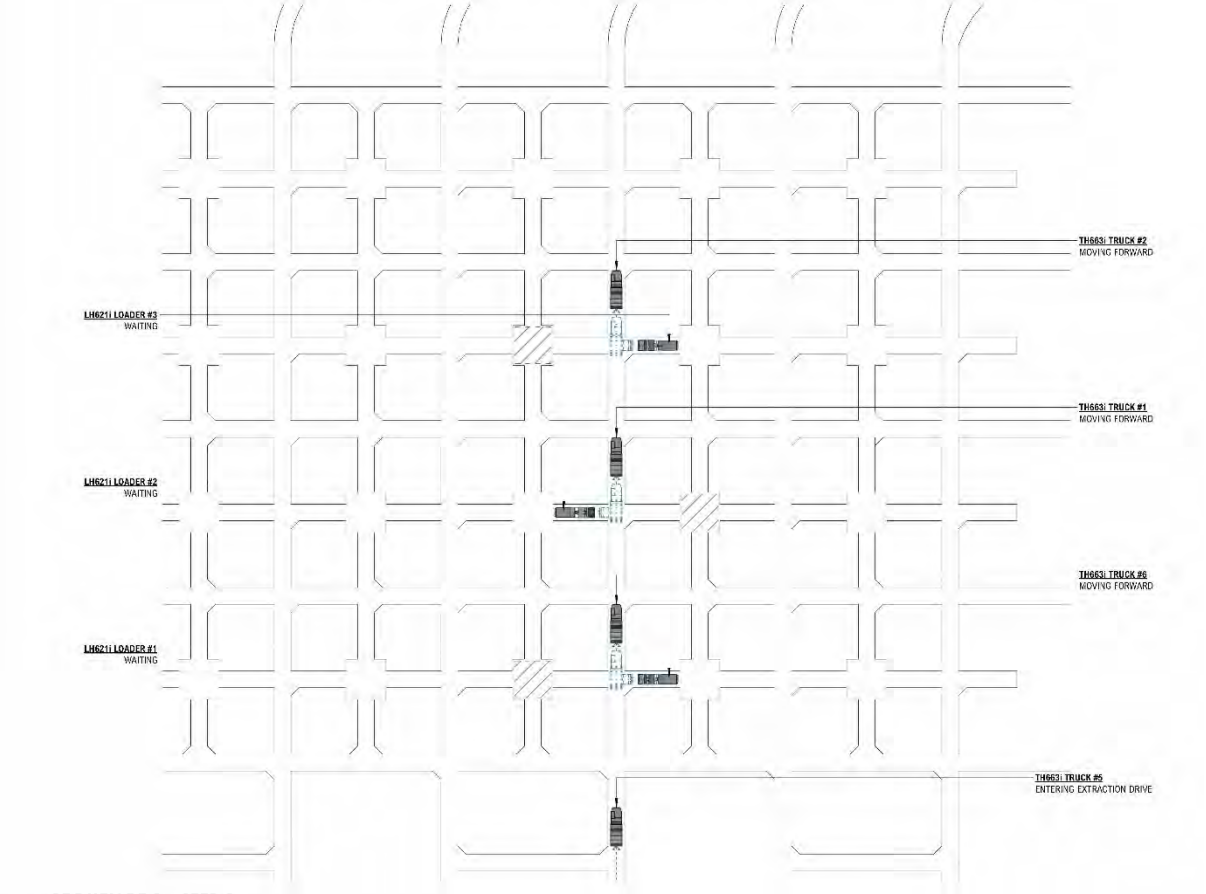

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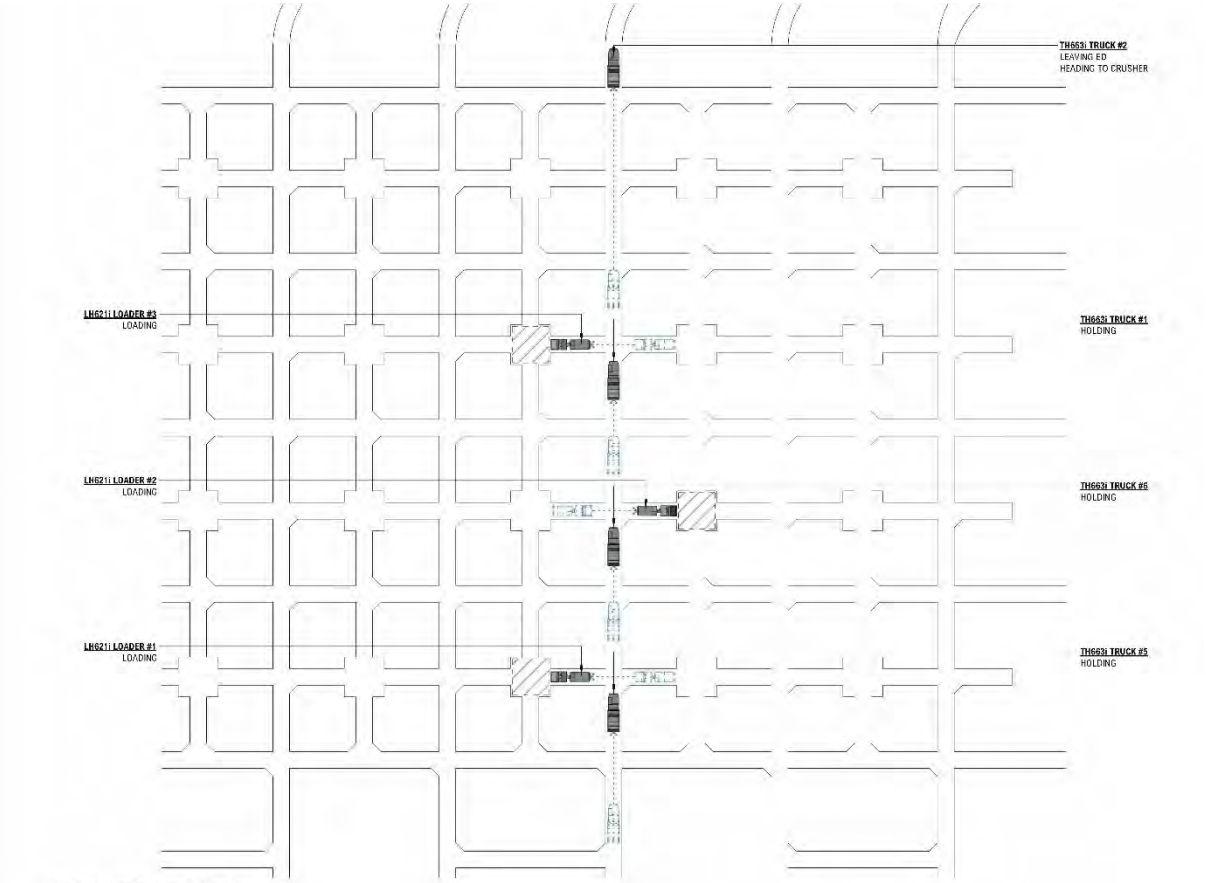

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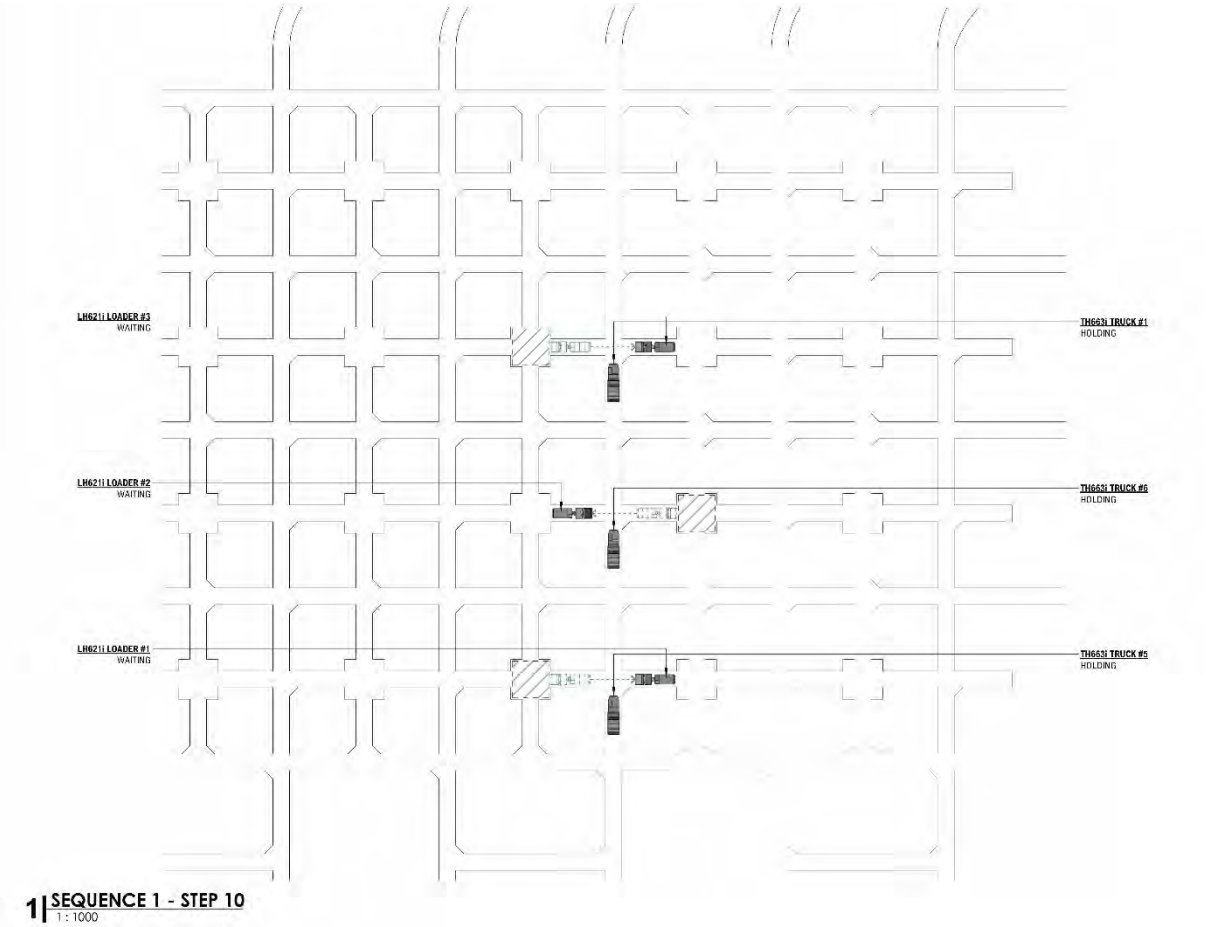

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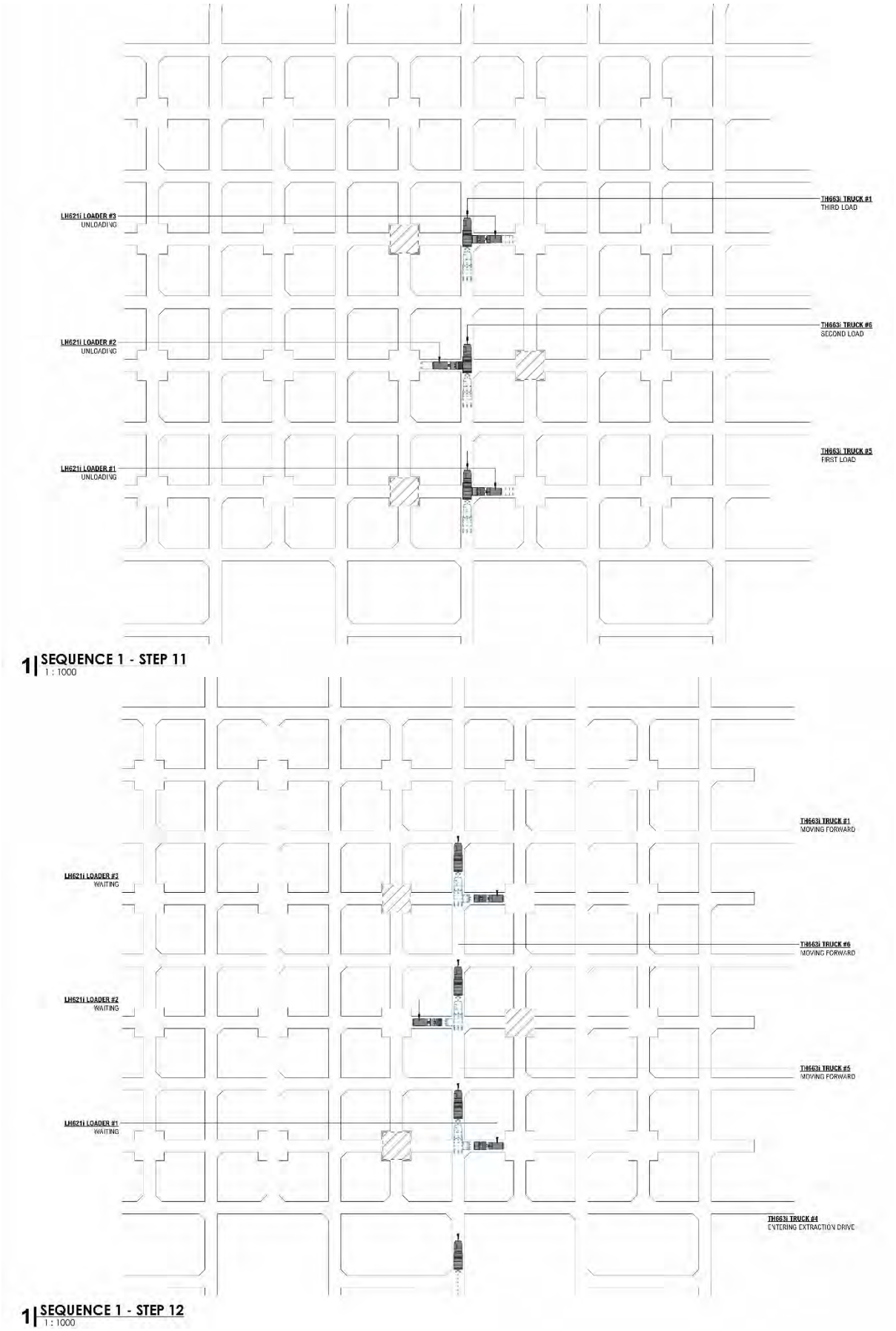
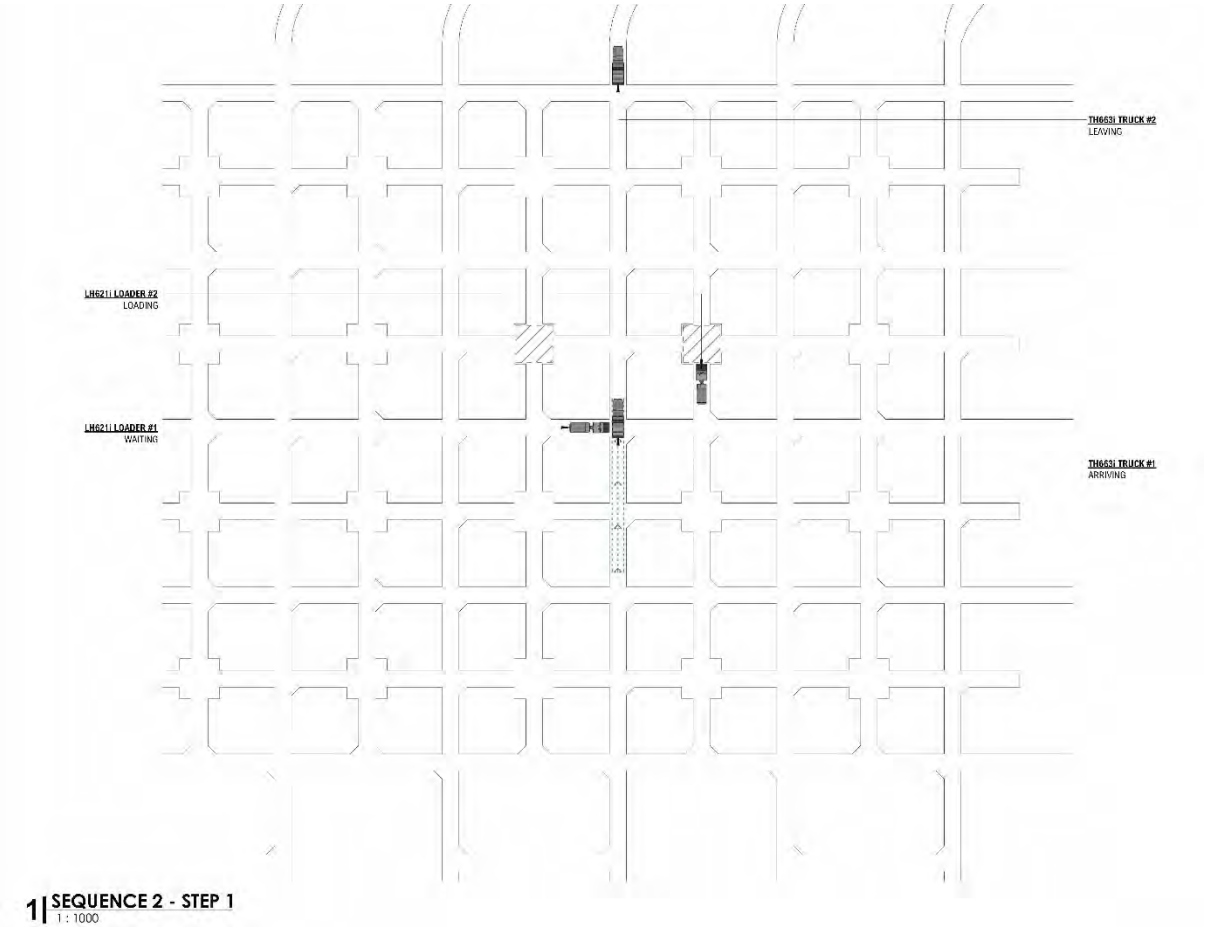


Figure 93: Truck and Loader Sequence 1 (Perpendicular Drawpoints)



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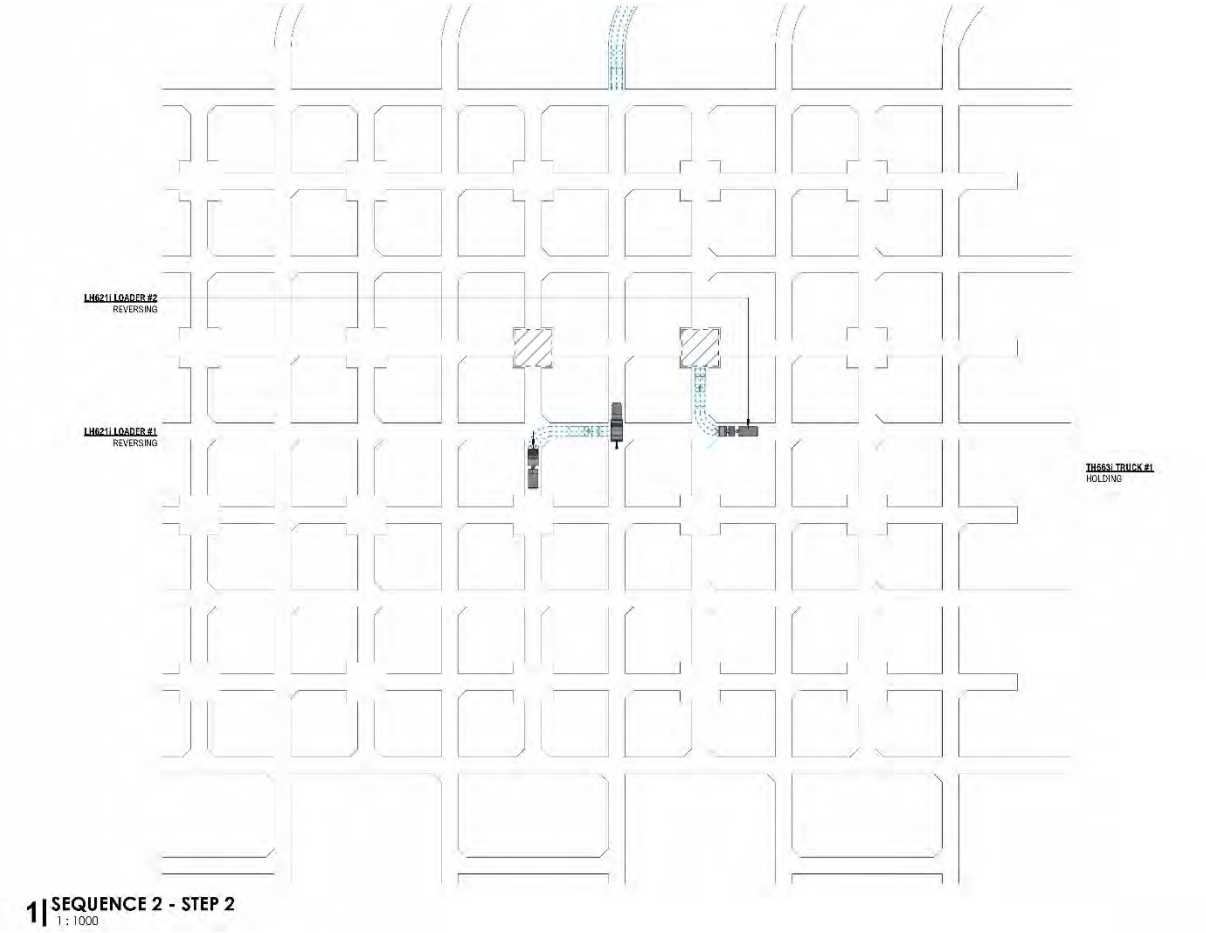

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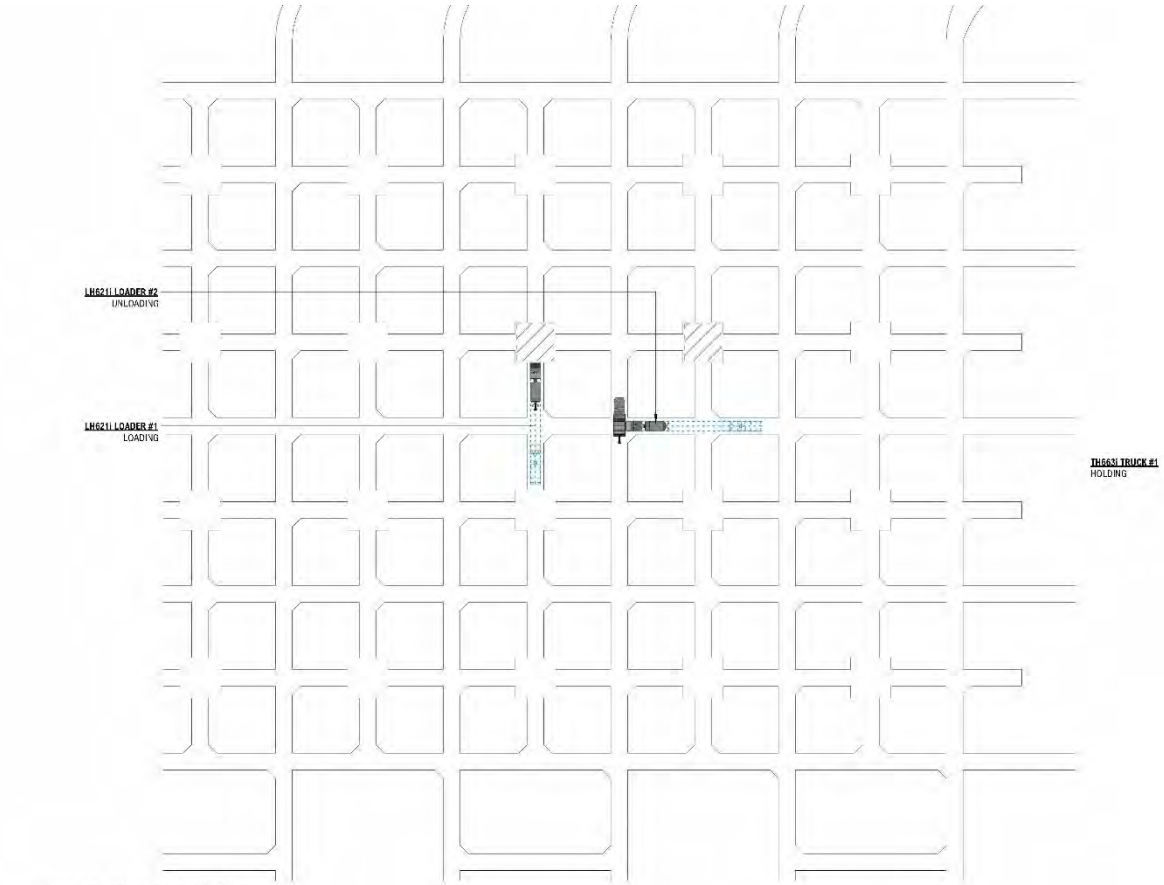

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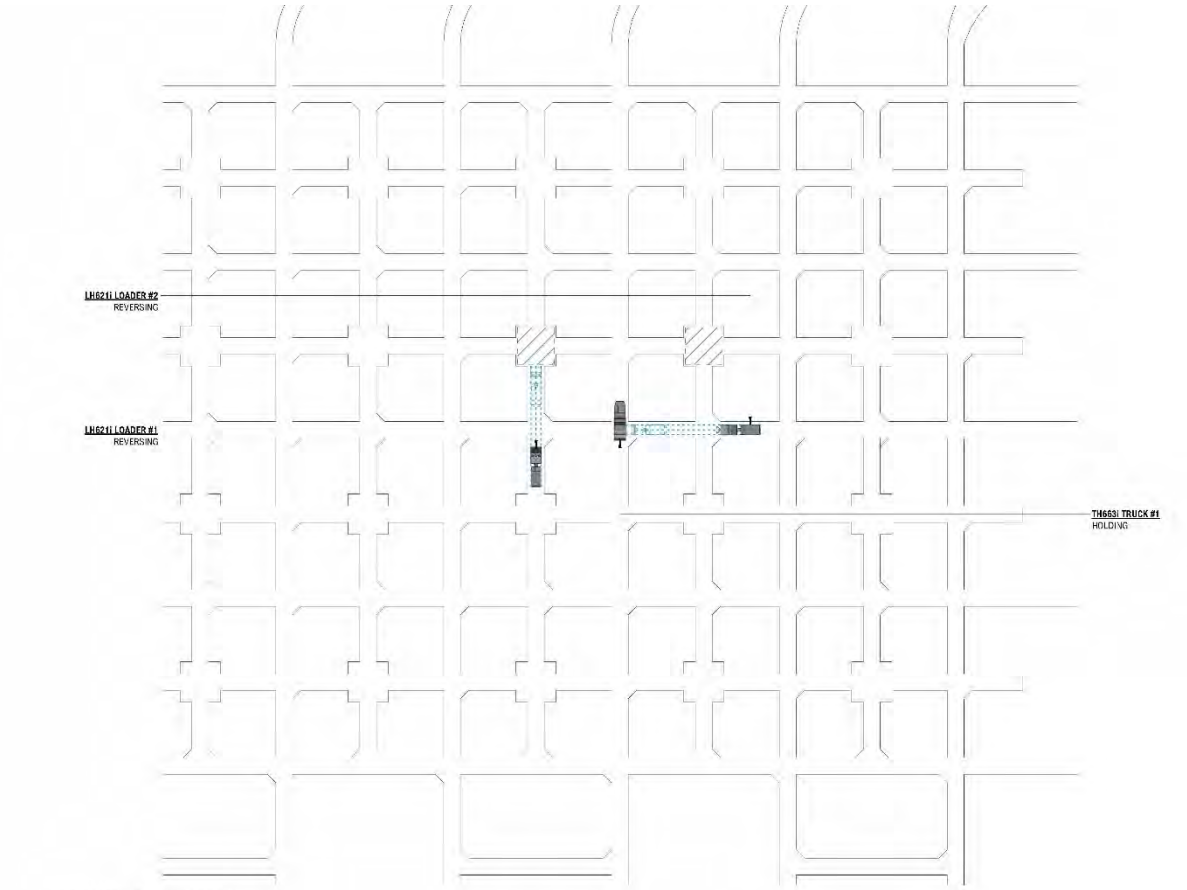

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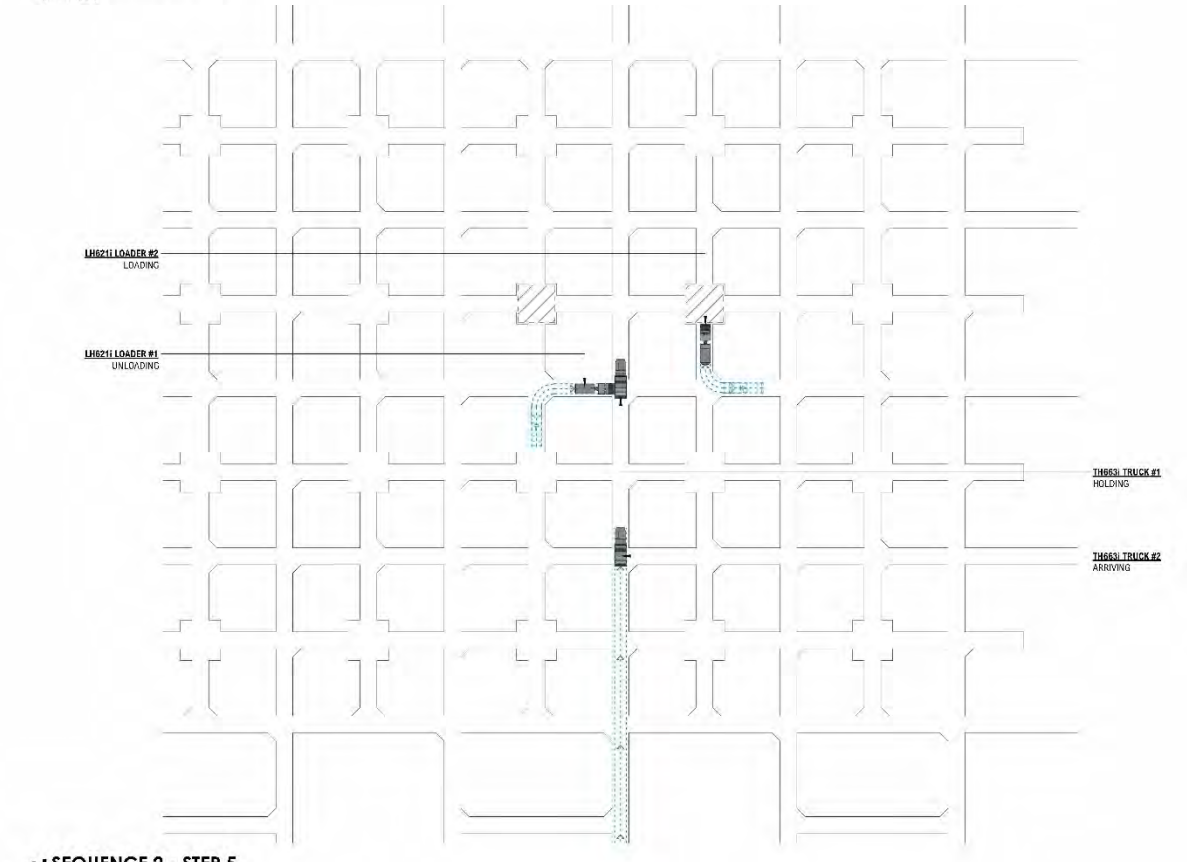

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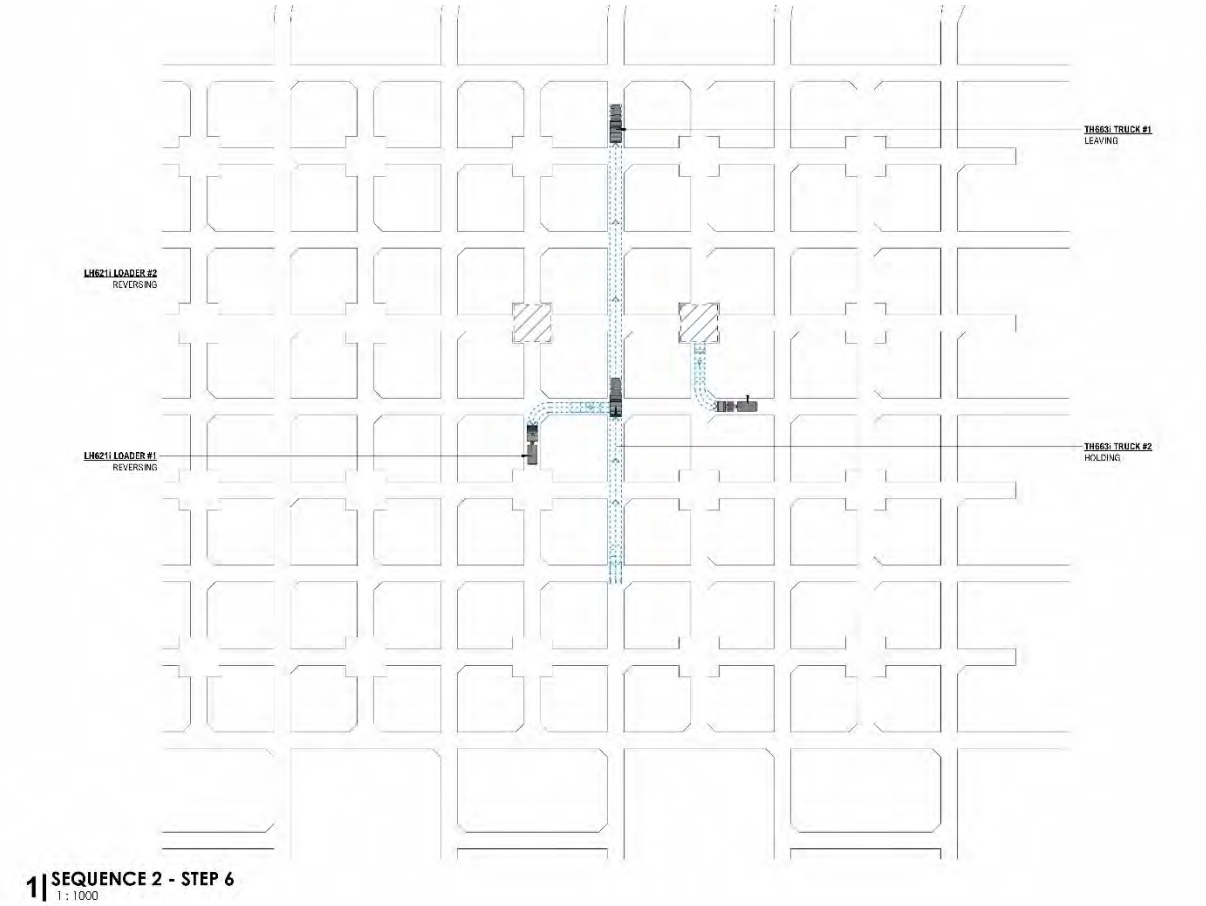

Figure 94: Truck and Loader Sequence 2 (Parallel Drawpoints)

7.3.2 Draw Strategies

Based on the overall lower truck loading times of the drawpoints parallel to the main Extraction Drives these drawpoints may have a slightly higher preference than the perpendicular drawpoints. This time reduction is due to being able to load a truck from two sides whilst the truck stays immobile. For the perpendicular drawpoints only a single loader can be used to load the truck and the truck is required to shuffle forwards to the next loading location, 3 per drive, to allow the loader to cross the Extraction Drive to enable it to load the truck.

The preference for the parallel drawpoints is in many ways similar to the existing El Teniente layout with its two drawpoints per drawbell. Even though the parallel drawpoints are preferred, the perpendicular drawpoints add the option to assist in the removal of oversize material and to generate wider drawzones above the drawbell.

The random draw strategies applied in the ore flow simulations showed that drawing from many drawbells results in a reduction in the height of interaction between the drawbells and generates a wider recovery zone with a smaller low flow area between drawbells.

To achieve the targeted 100,000tpd it was identified from the production simulations that 7 load units were required to extract the cave material from the 112 drawpoints on the footprint. This equates to an average draw of approximately 900 tonnes per day per drawpoint or ~500mm per day across the entire footprint. With the loader allocation requirements for the two drawpoint styles, parallel and perpendicular to the Extraction Drives, the general loader allocation for 7 loaders would be 3 to an Extraction Drive with perpendicular loading and 2 pairs in 2 Extraction Drives with parallel loading. The loader dispatching software, such as ORB by Polymathian, would be set up to sequence through the drawpoints to achieve the short, medium and long-term draw targets for the footprint whilst allocating the loaders, trucks and secondary break equipment as required.

The possible production rates available for the new footprint design and operating strategy are considerably higher per square metre than those possible on the existing footprint designs and as such the daily draw rates are larger than the existing industry parameters (Figure 95). Given that the material to be drawn is broken and sitting in the cave column, there is no operational or technical reason why the higher draw rates cannot be achieved. There are draw restrictions in the early stages of the cave when the cave is propagating to ensure the airgap is manageable and that the cave is propagating in the target locations, but once these conditions are removed the cave draw parameters are less prescriptive and are more focused on ensuring the maximum grade recovery from the cave over time and managing water and dilution ingress.

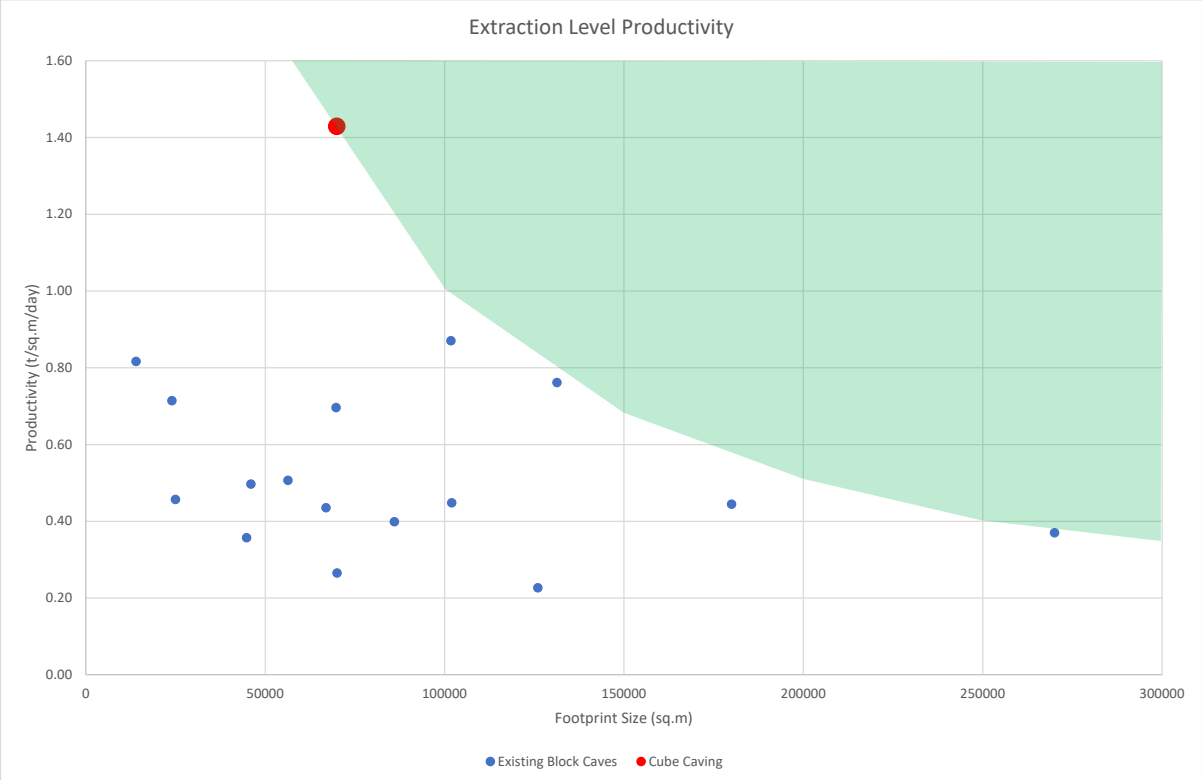

Figure 95: Productivity Benchmark assessment

7.3.3 Level Automation

The layout lends itself to automation with the simple traffic management of the one-way trucking loops and the loaders being contained within a controlled environment and not having to tram at high speeds in either loading configuration, see Figure 96 and Figure 97.

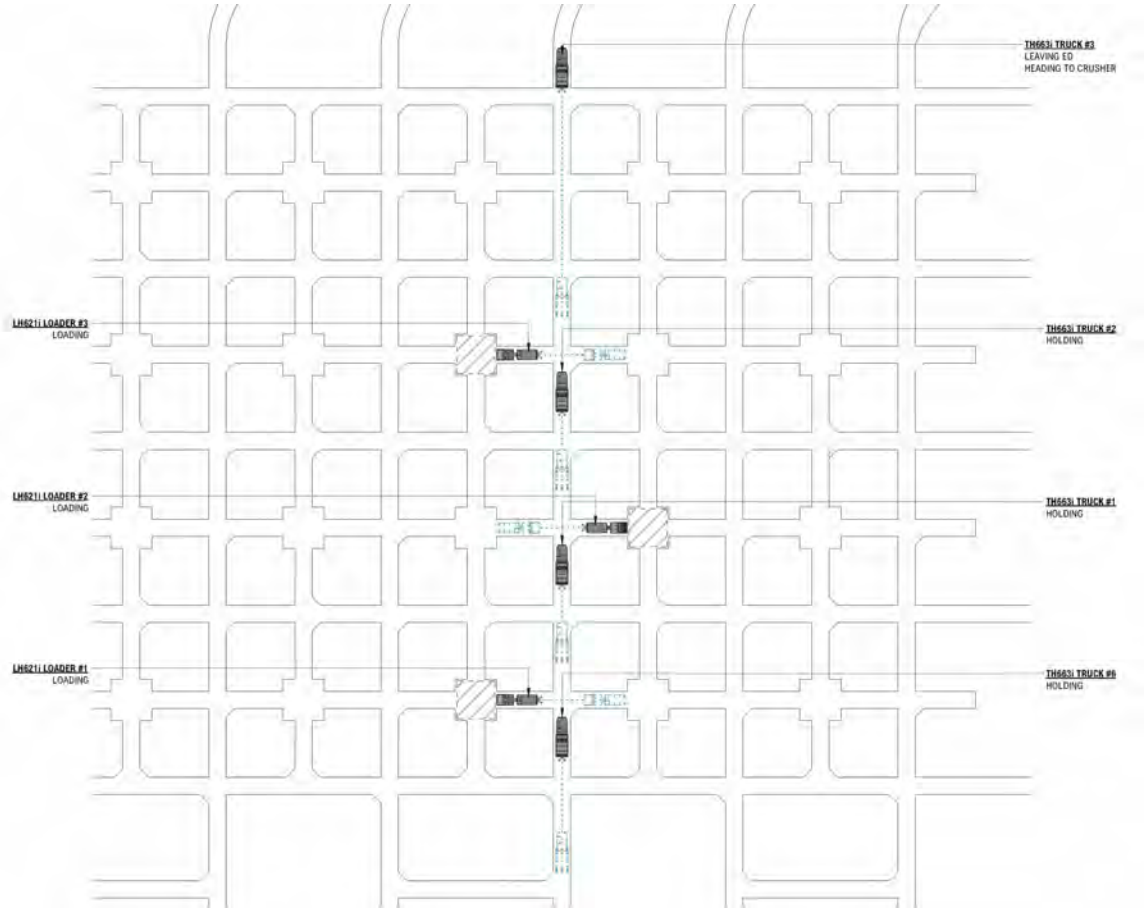

Figure 96: Truck and Loader movements for perpendicular drawpoints

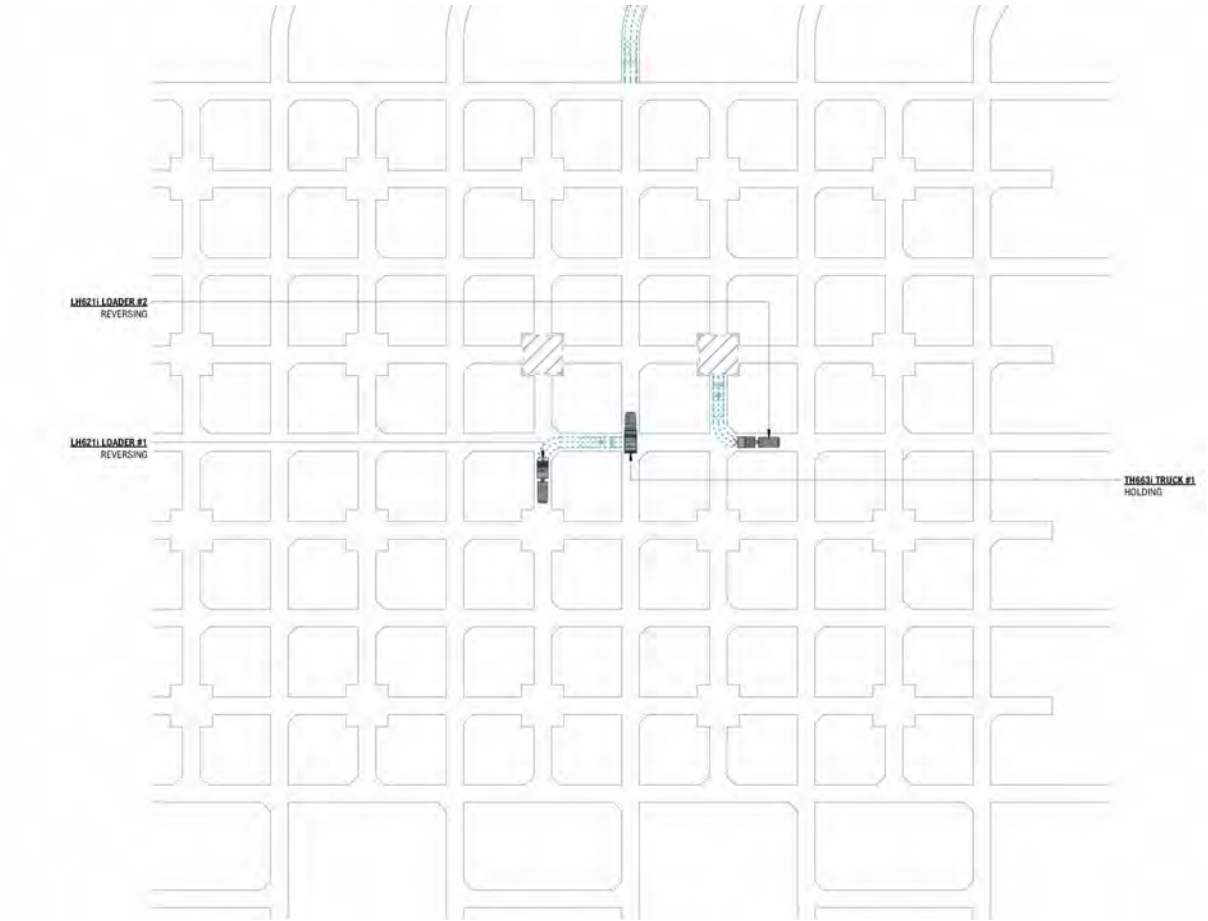

Figure 97: Truck and Loader movements for parallel drawpoints

7.4 Labour Requirements

There is a reduction in highly skilled loader drivers in the new layout who are capable of operating their machines at high speed to maximise production on a daily basis. In the Cube layout the loaders are never in more than second gear and the key functions are loading the bucket in the drawpoint rill and discharging it in the back of the truck, tramming is a minimal requirement.

The Secondary Break requirements are simplified to just treating the material >4m^3 which is expected to be done using drill and non-explosive techniques. This reduces the skill set normally required as part of a secondary break team with no rock breaking and other similar equipment in use. Water cannons will still be used to treat groups of fragments locked within the drawbell.

The truck fleet can be manual or automated. If manual, then the skill set required is less than that of a truck operator during the construction period, when there are a lot more equipment interactions and active loading locations. For an automated fleet there will be a requirement for system technicians and communications personnel to ensure the safe and continuous operation of the automated fleet.

Fleet maintenance will be based on the type of fleet selected i.e., manual diesel/automated diesel/manual electric (battery)/ automated electric (battery). The base fleet utilised will be manual diesel so the standard industry skills will be adequate. As the mines choose to upgrade their fleet and operating logic then the maintenance team will require upskilling, Original Equipment Manufacturer (OEM) support is expected.

Short interval control operators will be required to monitor and intervene as necessary on the footprint operating system. Many of these skills exist within the current Mine Operating Centres.

7.4.1 Training Requirements

No additional training requirements are required as the Cube layout utilises existing equipment in standard operating conditions. Should the equipment and technology utilised on the footprint change then upskilling of employees will be required as necessary.

Chapter 8

8 Equipment and Technology

8.1 Mobile Equipment

8.1.1 Development units

Drill and Blast

The entire layout and associated infrastructure can be developed utilising existing development equipment from Epiroc, Sandvik (Figure 98) or others. The consistency of profile and straight line development allows for the use of longer round techniques, long rail boring only jumbos supported by dedicated short rail bolting units, to reduce the overall number of “cuts” required to excavate the footprint.



Figure 98: Sandvik DD422iE Development Drill option (Sandvik 2024)

The 90-degree intersections are not able to be mined by the longer rail jumbos, if utilised, and need

to be mined using a short rail jumbo from the ground support installation fleet. Due to the sequence of development for the Cube layout, the mining of 90-degree intersections is only required at the start of each drive as the intersections within the Extraction Level are formed by mining one drive first and then breaking the perpendicular drive into it. This excavation strategy minimizes the damage at the intersections and enables additional ground support to be installed at the intersections prior to breakthrough.

Continuous Cutting

Opportunity exists to utilise mechanical cutting units in the future when they are proven to be a reliable alternative to the existing drill and blast units. The Cube layout is suitable to the mechanical cutting units (Figure 99) for the same reasons as the long rail jumbos.



Figure 99: Komatsu MC51 Continuous Cutting unit (Komatsu)

Ground Control installation

The ground support requirements for the Cube layout are in line with the existing industry standards and can therefore be installed by existing equipment (Figure 100).



Figure 100: Sandvik DS422i Cable bolt unit (Sandvik 2024)

With the likely deeper and higher stress environment of future caving projects the geotechnical requirements of the ground support will increase and require larger excavations to accommodate the thicker ground support whilst also still providing the finished profiles to allow larger equipment to operate. The large pillars designed in the Cube layout allow for wider development, if required, as there is still a substantial pillar core to transfer the cave loads and ground stress changes.

8.1.2 Production Drill units

The drawbell and undercut production drill holes are within the standard carousel capacities of the existing top hammer production drill offerings (Figure 101).



Figure 101: Sandvik DL422iE Production Drill Rig (Sandvik 2024)

The Post Conditioning downholes are larger, at 150mm diameter, and longer, at up to 105m, than standard but are still within existing equipment capacities. The Sandvik DU311-T In The Hole longhole drill (Figure 102) has a capacity of up to 254mm diameter to 150m. Additional air pressure will be required for the deeper hole lengths which can be achieved by installing a compressed air booster behind the drill rig. Deeper drilling was utilised to mobilise the wedge at Northparkes with 165mm diameter holes to 299m, (Hocking 2022).



Figure 102: Sandvik DU311-T ITH Longhole Drill (Sandvik 2024)

8.1.3 Explosives

Emulsion will be the preferred explosive product used during the development and establishment of the Cube layout, as it is the current industry preference due to its ease of transport, low noxious gas generation and water resistance.

8.1.4 Loading units

Payload

The drawpoint designs have been completed utilising a nominally 21t diesel loader (Figure 103). Continuous loading units similar to a Schaeff Super loader (Figure 104) or smaller capacity wheel loaders could be utilised if desired.



Figure 103: Production Loader (Sandvik 2024)



Figure 104: Terex ITC 315 Superloader (ITC SA 2024)

Digging Approach

Standard LHD style loading from the bottom of the rill and crowding back is the dominant method assumed for drawpoint loading. With the larger width drawpoints compared to the width of the LHD bucket a side to side loading strategy will also be required, this will enhance the width of movement and extraction within the cave material improving cave flow. The loader bucket entering the base of the rill and crowding back to fill creates a disturbance inside the rill when the loader retreats which generates movement opportunities for material within the cave column.

Continuous loading units use a top down approach with their excavator bucket to pull the material to the main loading area at the front of the unit. This scraping type approach results in less depth of disturbance within the base of the rill pile material, likely generating less movement within the draw column.

No work has been done to identify if there is any impact on the movement and extraction zones inside the cave column with the varying loading styles.

Load only

The continuous loading units are only able to load material at the rill with some flexibility to move oversize material out of the loading zone for it to be treated later. If a continuous loading unit is used in the layout then the truck fleet are required to access the Link drives to access the loading units in the drawpoints parallel to the Extraction Drives.

The drawpoint drive is long enough to ensure that the articulated wheel loader is straight when entering the rill at the drawpoint minimising strain on the chassis.

Load and Haul

The reconfiguration of the haulage system to allow trucks into the Extraction Level means that the production loaders need to only travel (haul) a short distance, ~50m, from the drawpoint rill to the truck loading point. The loader is required to a make a maximum of one 90 degree turn between the drawpoint rill and the truck loading point. With the reduced tramming length the top speed of the loader is less important to performance than the breakout force and bucket loading capacity of the unit.

The requirement to load trucks means that the load units need to be able to lift their buckets to height,

as opposed to tipping directly to a crusher or ore pass where the bucket only needs to lift above the stop log, ~1.5m.

Clean Up

A dedicated loader will be utilised to complete non-productive tasks including clean up after loading or secondary breaking tasks have been completed.

A road sweeper attachment will be utilised on the IT to clean the concrete roadways to minimize damage to the roadway and equipment tyres due to spillage material from the bogging and truck loading cycles.

Energy Source

The layout is agnostic to the energy source requirements of the loading fleet. The base assumption of the thesis is that the loading units are large capacity diesel units as the current battery and tethered electric units are not as productive. In the future if battery or tethered electric units become as productive, or there is a legislative requirement to not use diesel, then these units can easily be substituted into operation.

8.1.5 Hauling units

Payload

The base assumption of the thesis productivity work has been that the truck fleet is comprised of diesel trucks with approximately 60 tonne payloads (Figure 105). This has the trucks matched to the loading units and requires three pass loading. This size truck results in a manageable number of units operating on the Extraction Level without causing congestion whilst achieving the 100,000tpd productivity target. These units are industry standard and are also a rear dump configuration for tipping at the ROM bin. They are also highly flexible and could move freely through the entire Extraction Level footprint if required.



Figure 105: Production Haul Truck (Sandvik 2024)

Alternative options for the haulage units included smaller 20 tonne haulage units from Volvo which matched a single loader bucket, however this resulted in a large number of units required to achieve the productivity target and they caused congestion and impacted the movement of other equipment around the Extraction Level. On the other end of the haulage capacity were road train configurations up to 160 tonne, similar to Oyu Tolgoi. Whilst these larger capacity units reduced the number of trucks operating they required side tipping at the crusher which, whilst possible, reduced the number of tipping points from six to two and they were less effective being loaded from the perpendicular drawpoints as they require eight passes to fill them which meant the trucks needed to shuffle forwards and backwards multiple times to be fully loaded. The road train configurations also required larger turning radii, which could be accommodated on the entry and exit of the production area but restricted their movement within the production area to just the Extraction Drives reducing the ability for them to manoeuver around an unplanned breakdown or blockage.

Dumping Configuration

The thesis design uses a rear dump configuration at the ROM as this is the industry standard for the 60 tonne trucks selected. Rear dumping allows for a minimum of two and potentially three dump points at each ROM bin, increasing the flexibility for the trucking fleet.

Side dumping at the crusher is possible and would reduce the discharge time, however it comes with

a reduction in the number of discharge points reducing to one per ROM bin. The existing trucking fleet tub configuration would require re-engineering to utilise side tipping but if it is deemed appropriate in the future then it could be incorporated into the crusher ROM design.

Energy Source

Diesel fuel is the basis of this thesis work for the haulage units. The currently available battery trucks are not of the same capacity or performance as the diesel units. As this technology changes there is the ability to convert to battery or electric haul trucks in the future.

The Extraction Level and the haulage drives to the crusher are essentially flat and do not require a considerable power effort to haul the material between the drawpoints and the crusher. The trucking loops are also common which allows for conductive style battery charging to be used outside the footprint for all the trucks in the fleet.

8.1.6 Secondary Break solutions

Secondary break activities for oversize material will predominantly take place in the drawpoint accesses to limit the amount of oversize moved around the Extraction Level. Due to the size of material classed as oversize in the Cube methodology being larger than existing standards as a result of the on-level materials handling strategy and crusher sizing, the material will mostly be treated with drill and blast. The operating logic behind this is that depending on the lithology of the orebody the oversize material will likely be competent as it has withstood time in the cave column and possibly post condition blasting that it will therefore be too hard for a mobile rockbreaker to split. By utilising a drill and blast approach the oversize material will be treated once and broken into numerous pieces.

The downside to drill and blast techniques is the potential for flyrock damaging infrastructure in the drawpoint area and if explosives are used the need to clear the area during blasting and re-entry times post the firing.

8.2 Fixed Infrastructure

8.2.1 Mobile Fleet Maintenance and Refuelling Options

Underground Mobile Plant Workshops

A mobile fleet workshop has been included on the edge of the Extraction Level outside the abutment zone (Figure 106). There are multiple access points to the workshop area including from the haulage loop, the decline and the Extraction Level. The variable access points are to aid in the traffic flow in and around the workshop for not only the mobile equipment but also the operational and maintenance personnel and stores deliveries.

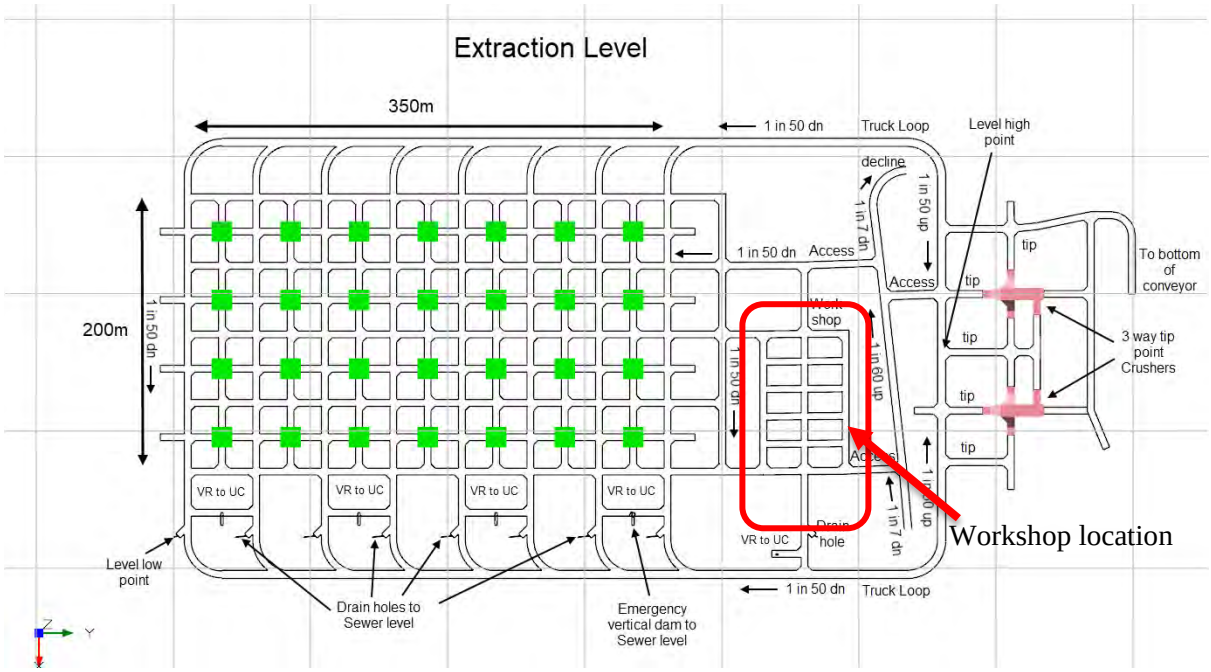

Figure 106: Underground Mobile Plant Workshop

The proposed workshop would be fitted out with the following facilities:

- Wash bay with oil and water separator,
- Service bays with overhead cranes,
- Service bays with underbody access, ramp style rather than pits,
- Lubrication storage and distribution to the service bays,
- Stores area,
- Light vehicle parking,
- Office and crib facilities, on the mezzanine level above the stores area,
- Refueling bay, with direct access to the return ventilation system, and

- Welding bay, with direct access to the return ventilation system

The workshop would initially satisfy the servicing requirements of the development and Cave Establishment fleets and then transition to the Production fleet.

Refuelling Options

Due to the currently unknown performance of battery equipment in the underground mining environment the basis of design for this thesis has been diesel loaders, trucks, service vehicles and light vehicles. Electric and battery units have been assumed for the development drills and ground support units (shotcrete rigs, agitators, ground support jumbos, cable bolters). Should the performance of battery production units be proven in the future then changeover is possible.

The refueling allowance in the workshop area is for diesel with delivery either via a fuel dropper system or fuel truck.

The electric and battery electric units are presumed to charge using 1000V when drilling or stationary in the heading thus not needing specific charging locations. The agitator units will be charged while delivering shotcrete to the spray units via a charging cable from the plugged in spray unit.

Allowances should be made in the power consumption calculations for the charging of the production units assuming advancements in battery technology. Conductive charging is also an option for these units via either in-floor or overhead charging configurations due the repetitive cycles the machines undertake.

8.2.2 Materials Handling System configuration

Drawpoint Infrastructure

At the drawpoint brow the infrastructure will include a beam, either stand alone or incorporated in to the ground support, to limit the length of the material rill into the drawpoint drive and water sprays to suppress dust generation at the drawpoint during loading. The drawpoint sprays will be installed utilising a modular type design for quick repair of damaged infrastructure.

There will be a barrier chain located in the drawpoint access to block off personnel access to the drawpoint for safety reasons. In the intersection between the opposing drawpoints, either in the Extraction Drive or the Link Drive, there will be a communication node to ensure connectivity with

the equipment and/or personnel operating in the drawpoints. This communication will provide position locations of personnel and equipment for task monitoring including draw control, collision avoidance and emergency contact.

Ore Pass Locations

There are no ore passes in the Cube layout. They are not necessary due to the use of the Post Undercutting cave establishment sequence where all production material is fired down towards the Extraction Level where it is transported using the highly efficient loader and truck configuration.

Primary Crusher(s)

In the working design of this thesis there are 2 equal capacity Gyratory style crushers installed to achieve the 100,000 tonnes per day (tpd) production rate. The gyratory crusher was selected as it not only generates a consistent shaped product for transporting on the vertical conveyances to surface, conveyor or shaft, it allows for multidirectional tipping into the Run of Mine (ROM) bin directly above the crusher. The ROM bin will have multiple tipples for the truck fleet to utilise, resulting in a total of up to 6 tipples being available to the trucking fleet, if required, or roughly 1 tipple per 2 operating trucks.

The layout for the proposed crusher stations is very similar to those utilised throughout the underground hardrock industry with the following features for performance and maintenance:

- A minimum of two and potentially up to three truck tip positions into the ROM box per crusher, each with a reinforced apron approach and stop log,
- Rockbreaker installed on a pedestal at the edge of the ROM box to treat any oversize that is inhibiting the flow,
- Local and remote-control locations for the crusher and rockbreaker,
- Crusher feed pocket below the truck tip level with LHD access for cleaning and spider access,
- Workshop area with an overhead crane for maintenance of the crusher and storage for a spare main shaft,
- Crusher eccentric access with trolley mounted maintenance platform,
- Covered lift well for access to the main drive motor from the workshop level,
- Crusher discharge pocket with dust extraction into the return ventilation system,
- Crusher Ore Bin (COB) with a live capacity of 15 minutes to enable continuous tipping, crushing or loading during short system outages,
- Tramp removal in the loading area, consisting of self-cleaning magnets located under the COB discharge, across the Collection conveyor, and then a metal detector located downstream of

this to alert of any metal which makes it past the two magnets and can then be manually recovered.

The decision to install two crusher units to achieve the 100,000tpd throughput rate instead of single unit is based on:

- The increased flexibility of the additional tipping points, 4 tipping points as a minimum with potentially up to 6 tipping locations between the 2 crusher units,
- Improved total materials handling system uptime in delivering ore to the surface due to one of the crushers still being available when the other is out for planned or unplanned maintenance. The only times the entire system will be down and not producing is when the vertical conveyance is offline. The estimated total system total time utilisation is 76.5% assuming 85% utilisation and each major component (crushers and conveyance system) having an availability of 95%.
- The reduction in capacity of each unit reduces the component size requirements making it easier to transport underground and assemble,
- The crusher chamber requirements are smaller for the twin units improving the integrity of the chamber and supporting excavations for the operation and maintenance of the crushers whilst also reducing the excavation time of the chambers.
- The crusher chambers will be sequenced to be mined and constructed sequentially to support the tonnage movement requirements during the Cave Establishment ramp up period.

Generically sized gyratory crushers in the 60” x 89” range (Figure 107) will have sufficient capacity to handle 100,000tpd with some margin and detailed design in a particular installation may permit smaller units.



Figure 107: Gyratory crusher cross section

The crusher chamber will be located outside the abutment stress zone created by the caving activities around the target ore block to ensure that the ground conditions are stable for the life of the asset. With the reduced size of the individual crushers to achieve the combined 100,000tpd, the chambers can be located closer to the active footprint than a large singular crusher due to the smaller stress disturbance created by the chambers. The other factor influencing the location of the crushers from the footprint is the location of the vertical conveyance to surface.

With the lateral haulage from the production drawpoints to the crusher being completed by the truck fleet, the distance from the footprint to the crusher tipping points is compensated for in the number of trucks utilised to move the target tonnage and does not impact the instantaneous productivity of the drawpoints or the overall footprint.

In the future, if additional mining areas are opened there is no requirement to install additional crushing stations as is the case currently for on-level crusher setups. Rather, additional trucks can be added to the fleet to cover the additional haulage distance and maintain the productivity rates thus significantly reducing the capital establishment of future mining areas whilst also providing sufficient materials handling capability to match the development and ramp up requirements of the new mining area.

Vertical Ore Haulage

For this thesis the assumed vertical haulage system is an inclined conveyor, though it is acknowledged there are numerous options available as listed in (Pratt 2008). An inclined conveyor can be scaled in performance to match the increase in ore production from the cave. The availability of a conveying system is higher than a shaft system due to the reduction in statutory checks required and with the tonnage rates targeted as part of this thesis there would be a requirement for multiple high-performance shafts.

The conveyor decline and transfer chamber development can all be completed utilising the same, or similar, development equipment to that utilised in the rest of the mine rather than very specialized equipment, and operational skills, as required to establish a shaft.

The improvements in conveyor belt technology over the last 20 years and the operational performance of high capacity and deep conveyor systems such as Cadia East provide confidence that the technology is available to support the production rates indicated in this thesis.

The conveyor system would be installed in a dedicated development tunnel which could also act as a second means of egress in the event of an emergency.

8.2.3 Supporting Infrastructure

Roadways

To improve the performance of the loading and hauling fleets, all roadways inside the Extraction Level and the roadways to the crushers will have concrete roadways installed. The roadways will nominally be constructed using a precast concrete panel design to aid in the installation and maintenance of the roadways.

Mine Dewatering

A dewatering system is required for a Block Caving mine to deal with water from three sources, notionally:

- Mine water, introduced to support development, drilling, dust suppression, etc.,
- Ground water inflows, and
- Precipitation entering the mine through the surface subsidence zone post breakthrough.

The majority of water would typically percolate through the cave column and report to the Extraction Level via the drawpoints. The ground water which enters the cave column from the sides and any surface runoff which enters the subsidence zone usually does not have the entry velocity to break the surface tension and reports to the drawpoints around the edges of the cave. The precipitation events, depending on intensity, may result in water build up in the surface subsidence zone and percolation through the full cave zone saturating the column as it goes.

The water reporting to the mine dewatering system will be classed as dirty as it generally has a significant amount of solids. It is critical that the dewatering system can accommodate potentially large inflows of dirty water from storm events post the cave breaking through to the surface. There are options available to create or utilise latent sumpage capacity within the mine to reduce the size of the dewatering infrastructure required for brief, but critical, periods in the mine's life.

The Extraction Level of the Cube layout is developed with gradients to direct the water to dedicated on level sumps and keep the drawpoint operational areas dry. During large ingress events the level is designed such that regular production operations are uninterrupted from the majority of the level whilst a portion of the footprint is utilised as the emergency sumpage to manage the inflows (Figure 108).

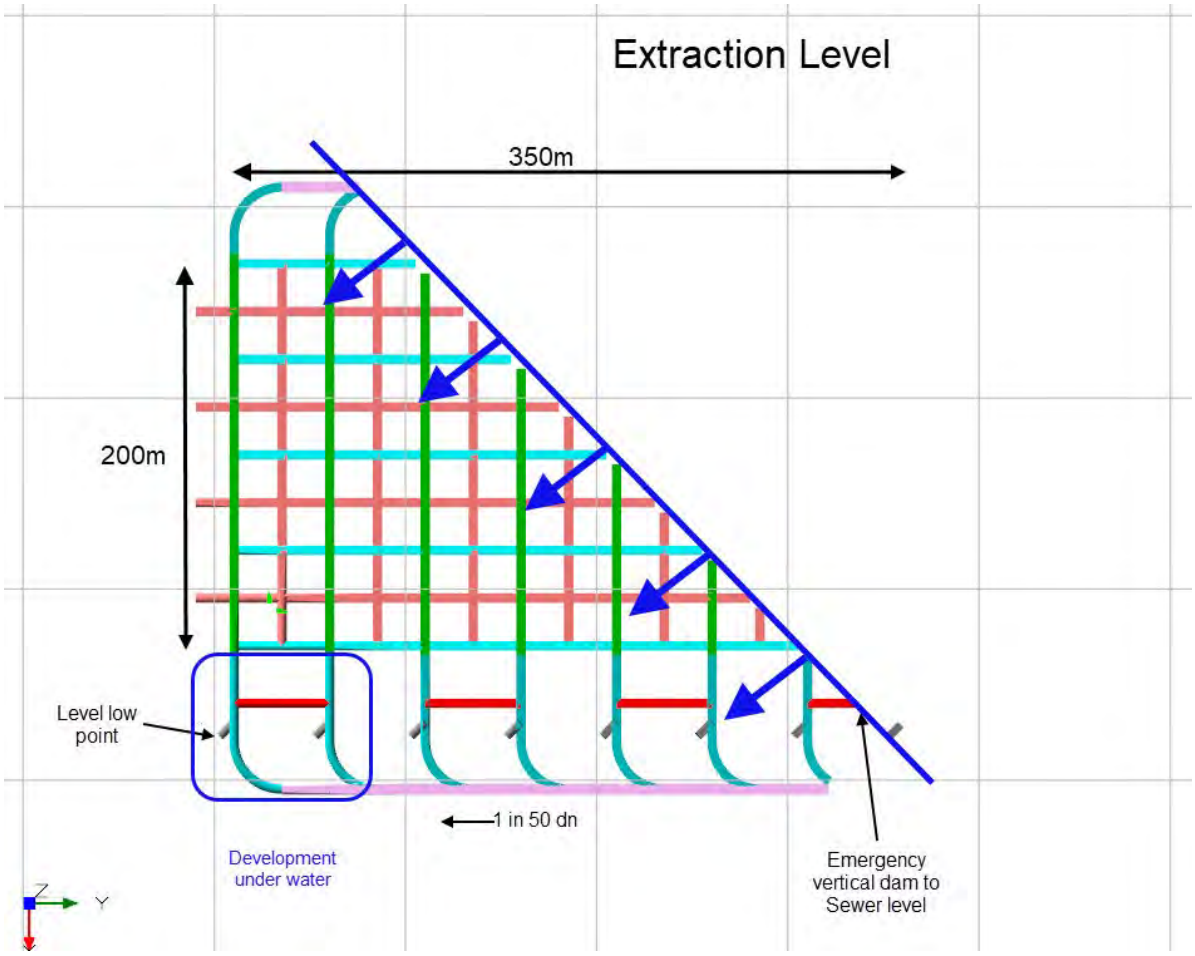

Figure 108: Extraction Level water levels during major rainfall ingress

An emergency vertical dam will be installed to limit the water height on the Extraction Level during large ingress events. This vertical dam would be linked to the pumping system and manage the high volume inflows during the limited duration event.

The dewatering system for a Block Cave mine of 100,000tpd would consist of high lift centrifugal or positive displacement pumps and a rising main circuit capable of accommodating the regular daily dewatering requirements of the mine in a likely duty/standby configuration. During slightly higher than normal water ingress the standby pumps could be engaged with the duty pumps to handle the higher water volumes.

Power

The High Voltage (HV) power configuration for the mine would be in accordance with the local regulatory requirements and be established as a minimum of one ring, and more likely two, through the mine to ensure continuous feed to the critical Fixed Infrastructure including the Primary Ventilation fans and heating and/or cooling infrastructure (if required), main pump station(s),

materials handling system and underground workshops and workforce facilities (offices, cribrooms, etc.).

Depending on the power source of the mobile equipment there may be a requirement for underground charging stations or conductive charging areas. These loads would be considered in the total mine power demand calculations to ensure there are no power interruptions to the rest of the mine during equipment charging operations.

Ventilation

The primary ventilation for the mine has been nominally designed using a pull exhaust system, meaning that there are primary exhaust fans located in the primary ventilation circuit which pull the air through the mine. The fans could be located on the surface or underground, at the base of the return air raises, depending on the electrical distribution, site security and noise limitations.

Communications and Control

The underground communications for the mine would be designed in a redundant ring manner between two surface communication nodes, utilising layer 3 ethernet switches. A fiber optic communications cable would follow the same route as the HV cable reticulation creating, likely, two underground communications rings.

The fibre optic cable would be sized to accommodate the desired communication and data transfers required to control the fixed and mobile plant within the mine and have room for future expansion.

Supporting Infrastructure

Underground refuge chambers, potable water supply, fuel supply and explosives magazines would be integrated to the mine design as per the local regulations and company requirements.

8.3 Discussion of Findings

The Cube layout is an agnostic design in relation to the equipment required to establish and execute it. The existing equipment available to the industry can undertake the development and cave establishment tasks associated with the Cube design meaning there are no new technologies required. As any future technology would need to be capable of similar performance to the existing product offerings these could be utilised when available.

The integration of zero emission equipment in the future is possible as the layout provides numerous locations for conductive battery charging, plug in charging and tethering of electrical cables if required.

Any advances in equipment technology can quickly and efficiently be incorporated into the Cube layout to enhance the productivity and efficiency of the mining operations. There are no equipment technology limitations envisaged with the revolutionary design developed in this thesis.

Technology can be utilised to enhance the safety, cost and productivity of the Cube Extraction Level. Examples include:

- The use of collision avoidance technology to enhance the safe working of personnel in the drawpoint areas with truck loading activities occurring nearby.
- The use of autonomous loading and haulage, over shift change to increase the operational hours of the Extraction Level or fully to remove personnel from the repetitive production tasks of drawpoint loading and transporting the ore from the drawpoints to the crushers.
- The use of equipment monitoring systems to provide key machine health data to enable proactive maintenance of machines rather than reactive breakdowns.
- Position location systems to track material movement and aid in real time dispatching of equipment to maximise the instantaneous production from the Extraction Level and materials handling system.

Chapter 9

9 Real World Comparison

9.1 Data Collection from Industry Case Study

A preliminary comparison of the Cube layout to that of a Feasibility Study level design El Teniente footprint was carried out at Carrapateena.

9.1.1 Description of Deposit

Carrapateena is a sub vertical orebody which is currently being mined top down utilising Sub Level Caving (SLC). The SLC was commenced in 2019 at ~500m below surface, and is extracting the higher grade portion of the deposit at a production rate increasing to 5.5Mtpa and will continue to a depth of ~1,000m below surface. Following a Pre-Feasibility Study into the lower section of the deposit a decision was made in 2020 to convert the next 500m of the deposit to be mined using the Block Cave method and to increase the production rate to 12Mtpa.

9.1.2 Key Technical Information

The Carrapateena Block Cave layout is at 1,500m below the surface (~500m below the base of the SLC). The footprint will utilise an El Teniente layout with 32m x 22m spaced drawbells and a Big W undercut, Figure 109, executed in a combination of Post and Advance undercutting sequences. The rock mass conditions are generally Good though there are some structures on the footprint and the North West corner contains potentially Poor to Very Poor ground as a result of a mine-scale structure. The virgin rock temperatures on the footprint are expected to exceed 70°C which will have impacts on personnel and equipment.

The base plan for the footprint is to utilise diesel 21t loaders and tip directly to an effectively on-level crusher via a vertical Run of Mine (ROM) bin. There is an option to operate 18t Battery loaders to show a pathway to the company's Carbon Emission targets.

The complete footprint is 14 Extraction Drives wide and is mined in two sections, BC1 which is 8

drives and BC2 which is 6 drives. BC1 is targeting the highest grade material between the footprint and the SLC and is planned to operate at 12Mtpa. BC2 is the lower grade edge of the deposit and is planned to operate at 8Mtpa.

The footprint has a single on footprint Jaw Gyratory crusher and due to the tramming distances from the far drawpoints the Extraction Drives will be operated as pairs to enable up to 6 loaders in 2 drives at any given time operating in a loop. This novel approach to the LHD tramming configuration has been incorporated to manage potential tyre issues due to the rock temperatures and also the lower payload capacity currently available in battery LHDs.

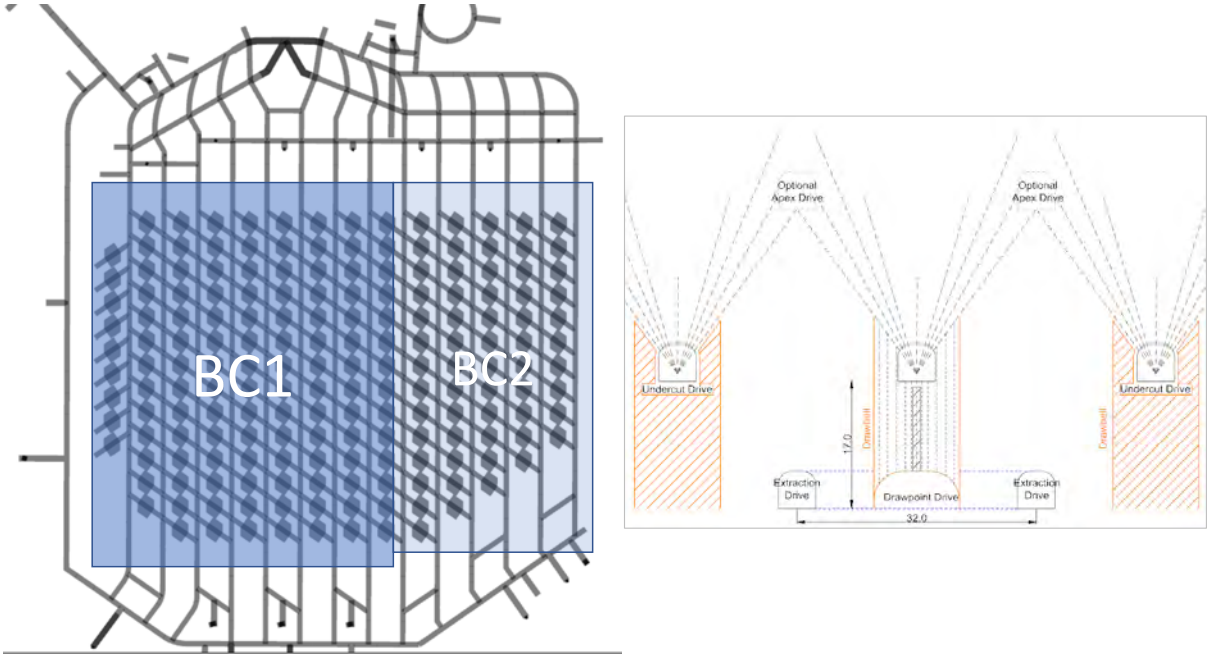

Figure 109: Carrapateena El Teniente Layout and drawbell section

9.1.3 Mine Establishment Schedule and Costs

The targeted ramp up duration from the first drawbell firing to the nameplate production is 44 months which on the latest schedule is 2031. The last 12 months of the ramp up are impacted by removing Extraction Drives from service for the installation of permanent services, including concrete roadways, which directly impacts the number of available drawpoints and haulage route options. The comparison schedule completed for the Cube design showed a material improvement in the ramp up to nameplate production with it achieved in 21 months or in less than half the time (Figure 110). The Cube establishment sequence was not impacted by the installation of permanent services as there were sufficient drawpoints and haulage routes available to maintain the production rate while completing these tasks. This difference in achieving nameplate production had an associated revenue increase for the mine of just under $1 billion.

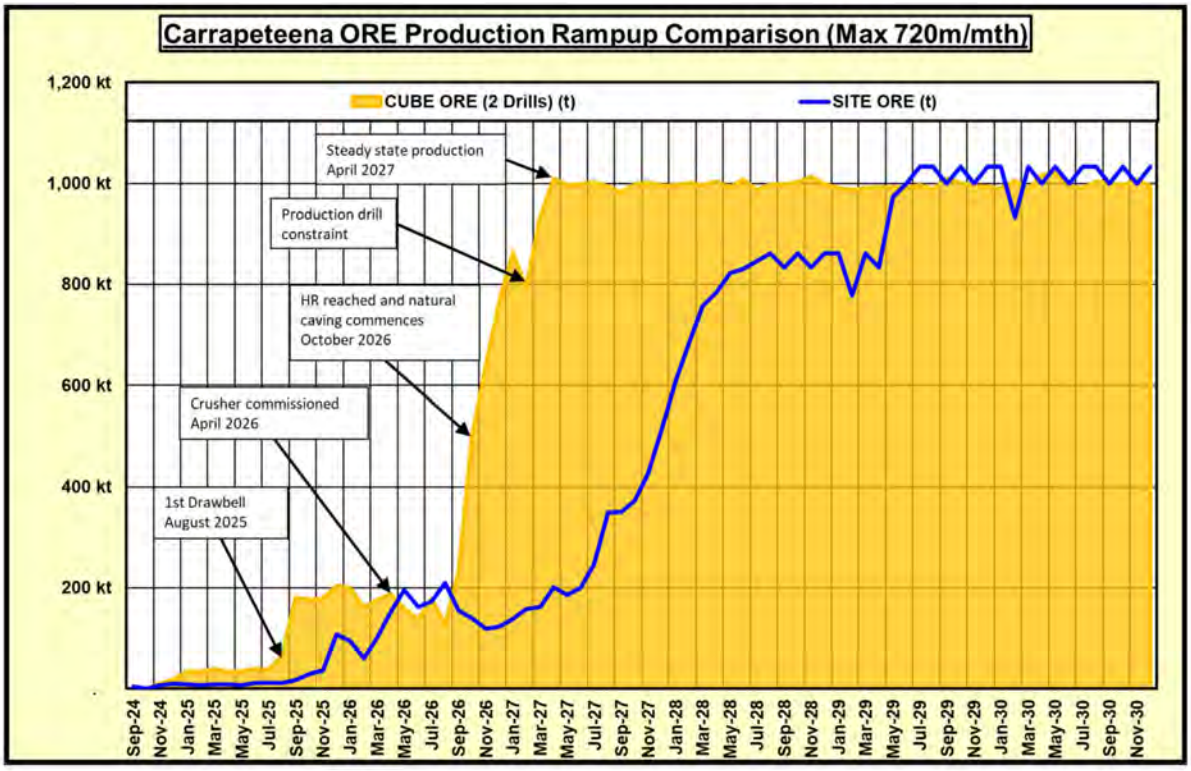

Figure 110: Ramp up schedule comparison for Carrapateena

9.2 Technical Assessment of New Design

The layout was redesigned using a 50m by 50m Cube layout, Figure 111, to enable the use of 21t loaders and 65t trucks. All infrastructure was kept consistent with the base plan and only the active mining areas of the Extraction Level and Undercut Level were adjusted to minimise the scope of the redesign. With the hot operating environment, the conversion to a truck fleet doing the hauling of material was identified as a material risk mitigator to tyre damage and equipment performance impacting the production rate. 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 than 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 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 LHD's were required to operate at a reduced capacity and therefore additional units were required to achieve the production targets.

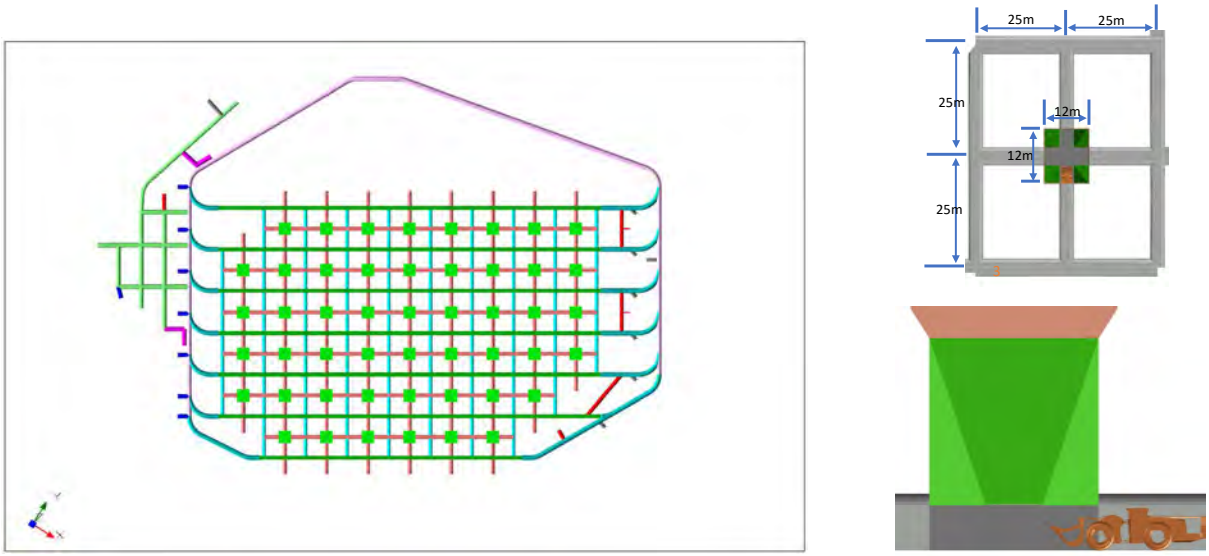

Figure 111: Carrapateena Cube Layout

9.3 New Design Schedule, Costs and Financials

The redesign and rescheduling of the mining areas resulted in:

- A reduction in the full footprint establishment cost of 20% or $100M from an original estimate of $485M,
- The inclusion of the 2 post conditioning levels and associated drilling and blasting added ~$50M to the Cave Establishment capital costs,
- A reduction in the footprint implementation time of 40% or 31 months from an original estimate of 75 months,
- An increase in cave ramp up and production which brought forward ~9.5Mt prior to 2030
- Productivity from the drawpoints is improved by ~100% and the production rate of 12Mtpa is achieved under all operating conditions, there is no production rate decrease from the BC2 section of the footprint
- The operating costs were reduced by 40 to 60% or $1.50/t (BC1) and $3.50.t (BC2)

9.4 Discussion of Findings

9.4.1 Comparison of Technical areas

The redesign of the Carrapateena Block Cave utilising the Cube design developed during this thesis results in a stable and reliable Extraction Level for the life of the footprint. In particular the Northwestern corner, which is influenced by a confluence of faults, is compromised in the standard El Teniente design and results in the use of large drawbell spacing for maximum pillar stability and varying undercut strategies across the footprint to manage stress redistribution with increased rehabilitation to maintain access to the crusher for the loaders during operation is expected to be stable in the Cube layout.

The loader tramming routes in the El Teniente design require the implementation of a non-standard loop strategy to enable the operation of three loaders in two Extraction Drives to achieve the 12Mtpa production rate. Whilst this strategy has been used to limited effect at Cadia East on PC1S1 it has not been attempted at the high tonnage rates and for the duration required at Carrapateena. The Cube layout utilising the truck fleet to haul from the loading points to the crusher is unaffected by the haulage distance as an additional truck or two can be added to the fleet if necessary.

The tramming speeds required for the production loaders in the El Teniente configuration will see significant heat build-up in the tyres which will be exacerbated by the hot operating conditions expected to be encountered at the 1,500m depth of the Extraction Level. If the tyre temperatures become excessive then the loaders will be required to slow down and additional units will need to be included into the circuit, increasing operating costs and congestion, and making it critical that the loop strategy works to enable the additional loaders otherwise the production rate will need to be reduced as there are insufficient pathways from the drawbells to the on-level crusher tip points. The Cube layout is more resilient in the hot operating environment as the loaders are only required to travel a short distance in second gear, thus limiting tyre heat. The trucking fleet may be impacted by the hot environment, however, it is relatively simple to add additional units into the system without causing delay should the speeds or load capacities be reduced to manage tyres whilst still achieving the desired production rate.

The flow and recovery from the Cube drawbells is expected to be the same or better than the proposed El Teniente layout as the comparisons completed to date have been on smaller spaced El Teniente layouts with similar fragmentation estimates. The increased stability of the Cube Extraction Level resulting in no lost drawpoints and limited rehabilitation that enables the desired production draw plan

to be followed whilst the El Teniente layout is expecting lost drawpoints over time impacting the instantaneous draw rates and the long-term total ore recovery.

9.4.2 Comparison of Schedule and Financial outcomes

The Cave Establishment schedule for the Carrapateena Block Cave was significantly reduced by utilising the Cube design when compared to the industry standard El Teniente design. The key contributing factors were:

- the reduced number of drawbell turnouts requiring smaller stripping cuts,
- the larger size, in area, of the undercut blasts reducing the number of overall firings,
- the increased ramp up rate to nameplate resulting from the larger volume of blasted rock
- The ability to install the final services on the level whilst still ramping up the cave production due to the haulage routes. This was not possible in the El Teniente layout with the installation of concrete roadways limiting the number of available Extraction Drives available and therefore limiting the production output.
- The improved ramp up brought forward more than a full year of production at nameplate rates for a significant revenue benefit during the payback period of the footprint.
- The Cube layout incorporated the BC2 component of the footprint in the initial establishment resulting in some lower grades being sent to the mill, though the trade-offs were
    - increased ore sources,
    - completing all development in one phase and not having to remobilise a workforce to establish the second phase footprint while producing at maximum tonnage rates from the BC1 area,
    - improved ventilation through the simplification of the footprint establishment phases, there is an increase in ventilation required when establishing BC2 whilst concurrently operating BC1,
    - improving the cave propagation through not having to establish a new cave against an existing one and therefore maximising the likelihood of achieving the final cave shape and ore reserve recovery.
- The operating costs of transporting the material from the drawpoints to the crusher is almost halved for the Cube configuration compared to the El Teniente configuration, this is driven by the fleet numbers and the lower operating cost per tonne hauled of the trucks compared to the loaders.

9.4.3 Technology Options

The Cube footprint is open to technology advances and can accommodate them within the establishment and operation of the footprint.

The footprint and haulage configuration suits the use of rechargeable batteries and electrified equipment.

Collision avoidance and equipment and personnel tracking systems can be used to aid in improving the safety, performance and cost of operating the Extraction Level.

Carrapateena is already utilising a real time equipment dispatching system for the SLC to manage the draw from the cave with plans to implement the Block Cave version of it, developed by the author at Cadia East, on the Extraction Level.

Chapter 10

10 Future Work

10.1 Areas for Further Investigation

The biggest unknown of the new design and operating logic for the Cube design is that at this stage it is entirely theoretical. Whilst there has been considerable computer modelling and simulation work carried out on the design and operating logic it is not the same as having a physical drawbell or two excavated from which actual data can be collected. The insights and feedback of industry experts in the fields of geotechnical and flow modelling and operational simulation have been incorporated into the revised design and operating logic of the Cube layout.

Specific areas of the design identified as requiring additional investigation during the research include:

- The relatively large firings required to establish the top section of the drawbell from the Undercut Level triggering a seismic response as the ground stresses redistribute. The current establishment of the drawbell has two firings, 750 and 1,250m^2, which are larger in area than a full El Teniente drawbell at ~720m^2. Preliminary work has been done on increasing the number of firings to reduce the potential impact of stress redistribution, though further detail of drill and blast design needs to be completed.
- The doubling of extracted tonnes per drawpoint will see an increase in the wear of the drawpoint brow. This has been accounted for with the vertical brow geometry to a height of 15m and the length of the drawpoint drive allows for approximately 2m of brow wear and replacement brow infrastructure before the back end of the LHD protrudes from the drawpoint drive and impacts vehicle movements in the Extraction and Link Drives.
- The loss of a drawpoint has not been explicitly modelled to identify the impacts on ore flow and the interaction of the multiple drawzones within the drawbell.
- The lack of flow over the diagonals of the drawbell. Whilst this is not seen as a material detraction in the design it does result in reduced ore recovery estimates and some pillar loading, both of which have been included in the assessments.
- Fine fragmentation within the draw columns could cause chimneying from individual drawpoints and limit the amount of interaction within and between the drawbells. This issue

is common to all Block Caving footprints though it is arguably more detrimental to the Cube layout due to the reduced number of drawpoints.

- Some of the flow software currently being used in the industry, CaveSim and FS4, is predicting wider draw columns than previously anticipated as a result of some draw marker experiments, advances in the understanding of what impacts fragment flow in a cave column and improvements in computer hardware and software. These wider draw cones enable the Cube layout to incorporate large pillars for stability without compromising ore recovery.
- The impact of material sitting on the fired extremities of the large, inverted pyramid component of the drawbell causing increased friction which creates a valley angle greater than the blasted 60° impacting the flow of material on the edges of the drawzones and potentially leading to cohesive arching. This is an issue in all drawbell designs and the large spans in this area of the Cube drawbell should mitigate the issue.
- Wet muck management protocols might require an entire drawbell to be placed on restricted access which would limit the travel in potentially 2 Extraction Drives and require remote loading to occur. The reduction in available Extraction Drives would not impact production as the simulations indicate that only 3 of the current 7 Extraction Drives are required to achieve the production target. The utilisation of remote loading in a manual trucking scenario would require more consideration to determine which path the loader takes to find a suitable truck loading location. Any wet muck spill would travel to the drawpoint directly opposite before, if the spill is large enough, rebounding and encountering further material in either the Extraction Drive or the Link Drive and likely traveling in both directions before meeting the nearest 4 way intersections and having the energy further dissipated.
- In achieving the productivity targets the number of trucks in use will lead to some queuing in the Extraction Drives and at the crusher tipples. Short Interval Control dispatching software is available to ensure the correct number of trucks are used for the loading locations and to reallocate the trucks as needed to minimize any delays. The trucks holding in the Extraction Drives may lead to slightly increased heat loads and short term ventilation impacts but should not impede other vehicles or tasks being undertaken on the Extraction Level.
- The trucks being loaded and operating in the level results in increased vehicle to vehicle and vehicle to people interactions. With the proposed operating strategy there is the opportunity for personnel or other equipment to be in a drawpoint when a truck passes it in the Extraction Drive. These can be managed by administrative controls or with the inclusion of collision avoidance systems. Additional controls could also be the use of remote controlled or autonomous loaders and trucks which would remove personnel from the operating environment.
- Spillage in the Extraction Drives of a Block Cave is not new, as material will fall from an

overloaded LHD bucket. In the Cube layout with truck loading occurring inside the production area on the Extraction Drives there is the opportunity for greater spillage which can impact tyre performance and impede autonomous operation. An allowance has been made for a small road cleaning unit in the equipment list to support production activities.

- The Link Drives provide open connections between the Extraction Drives which result in a less-than-ideal ventilation network. To enhance the limited flows through the Link Drives when the loaders are operating will likely require the inclusion of a jet fan in the Link Drive to assist in moving the air between Extraction Drives.
- The effectiveness and timing of the post conditioning. The blast holes have currently been designed to eliminate any rock fragments >10m^3 in the lower portion of the cave columns, though with this came the realization that there was now considerable blasted material available during the ramp up period. The challenge with the proposed concept is the large blasts will have a considerable impacts of the ground stress redistribution and will likely cause seismic events that result in exclusion limits around the blasted area. Should the blasts induce seismic events which have a negative impact on the Extraction Level establishment or if the cave begins propagating faster than expected then they can be halted. Geotechnical modelling of the stress changes associated with the firing of the Post Conditioning blasting needs to be conducted.
- Incorporation of new technology for:
    - the excavation of the Extraction Level to further improve the integrity of the pillars,
    - collision avoidance and personnel tracking whilst loading the trucks and operating secondary break activities within the drawpoints perpendicular to the Extraction Drive whilst trucks are operating
    - the use of wireless electronic detonators in the ultimate drawbell, undercut component, and post conditioning blasting areas to minimise the need for personnel to return to hazardous areas post blasting. The implementation of pre-charging would enable the use of wireless detonators in these areas.
    - Reduction of diesel emissions by using electric, hybrid, battery or other forms of greener energy power units for the truck and loader fleets in particular
    - The scheduling and short interval control of the cave establishment and production activities to provide the site teams with the greatest chance of success
    - The removal of personnel from high-risk areas using automation or remote operation. The stability of the Extraction Level enables the installation of high-performance communication networks to assist with the data transmissions required for effective machine control and visibility of tasks.
    - Installation of cave flow and cave establishment markers to track the stresses and

movement of material as the cave is initiating and propagating to understand the differences, if any, in the behaviour of the cave.

- Review flow code logic to improve confidence in ore recovery from a four-sided drawbell and incorporate the information gathered from the cave flow beacons into the software predictions for ore recovery.

Chapter 11

11 Conclusions

11.1 Conclusions

A new design configuration for a Block Caving mine was developed in this thesis. As part of the process, original contributions were made to the understanding of Block Cave establishment scheduling and the productivity constraints of the operational caving layouts. These breakthroughs came from critical reviews of the available literature and data plus the design, establishment and operational knowledge of the author. In the process a novel 4-sided drawbell was designed and enhancements were made to existing industry software to evaluate the gravity flow impacts of the new design approach.

The key system requirements in the establishment and operation of a Block Caving Extraction Level are nominally (Arancibia, Carrasco et al. 2008):

- Stability
- Ore Recovery
- Dilution management
- Productivity
- Materials handling system restrictions

Through the research completed during this thesis the initial Research Questions have been addressed and answered.

1. *What needs to change, in the design and establishment of caving footprints, to enable a reduction of 30% in the time taken to achieve nameplate production, without compromising the long-term productivity of the footprint?*

Through the thesis process it was identified that several items needed to be changed to deliver an approximate 40% reduction in the Cave Establishment time, including:

- simplifying the geometry and development profiles on the Extraction Level, the majority of the level could be completed utilising long-round advance which improved the total development time through reduced firings,

- The predominant reallocation of production drilling to the Undercut Level further reduced congestion on the Extraction Level,
- The redesign of the drawpoint length which enabled a machine to be fully off the Extraction or Link Drive enabled unhindered equipment movement around the level which further improved the schedule. The largest impact of this was during the establishment of permanent services, including concrete roads, where enough travel ways were available for production to continue ramping up whilst other activities continued,
- The larger undercut area and volume blasts enabled by the 4-sided drawbell redesign offer the opportunity to undercut the footprint at rates more than double the industry average, if the rockmass can accommodate the stress changes, and
- The introduction of the two post conditioning levels provides the first few years of production material as coarsely blasted improving the early draw rates available to achieve nameplate.

2. *What are the key economic parameters that influence the economic performance of a Block Caving mine and how can they be revised to improve the economic returns?*

During the thesis work it became evident that the cave ramp up had the largest influence on the economic returns of the Block Cave footprint. During the real-world analysis of Carrapateena there was approximately a full year of production brought forward in the first 4 years of production with a value roughly the same as the underground project investment, thus materially reducing the payback period and improving the Project economics. The other influences were the reduction in cave establishment scope and duration reducing the capital investment cost, followed by the reduced operating cost. Whilst it is difficult to validate the impact of the improved stability and reliability of production forecasting along with reduced rehabilitation on the footprint, these were also thought to contribute to the improved economics of the mine.

3. *Which technical areas have the largest influence on the successful extraction of the target ore block and how can they be enabled in the mine design and execution strategies?*

The technical analysis conducted during the thesis identified a few technical areas, including

- that the stability of the Extraction Level has the largest influence on the successful extraction of the target ore. If a drawpoint is lost, through ground instability, the influence can spread, and portions of the footprint become inaccessible, or production is reduced to correct the issue.
- The shape of the drawbell, including the undercut geometry, determines the near field draw of material from the cave, whether there will be any no or low-flow zones which will potentially create span interrupts and stall the caving process. It also determines how the

material will present at the drawpoint and what fragment size can be accommodated.

- Cave fragmentation and the presentation of material at the drawpoints influences the production rate during ramp up but also the geometry of the extraction and movement zones which determine the stress redistribution in the cave column and the drawdown of the cave material.

4. *What design and operational strategies are available to minimize, and ideally eliminate, major hazards from a Block caving footprint?*

During the thesis work the reduction of caving hazards was considered at each design, implementation and operation step. Whilst it is unlikely that caving hazards can be eliminated, due to the variability of the rockmass and the scale of stress redistribution due to the caving process, they can certainly be reduced. The key hazards reduced during this thesis work were:

- Airblast, through the inclusion of the 2 post conditioning levels the natural cave back is moved over 200m from the Extraction Level and there is a blanket of 200m of blasted material to buffer the air movement to the Undercut and Extraction Levels.
- Inrush, including mud rush and fines rush, through the geometry of the drawpoints there is a retreat point beyond the Extraction or Link drive of every drawpoint allowing machinery to be removed to safety. The retreat distance is more than double that currently available in the industry
- Personnel and Vehicle interactions, these have been reduced through the design of the drawpoints being long enough to enable a vehicle to fully enter and allow another vehicle to pass. The drawpoints are at 90 degrees to the Extraction and Link drives reducing the likelihood of a machine inadvertently entering a drawpoint, unlike the existing 50 to 60 degree turnouts. The single direction traffic flow of the trucks and other equipment through the Extraction Level reduces the chances of a vehicle on vehicle interaction. Further, the loaders now only operate in 2nd gear due to the reduced tramming requirements improving the stopping distance and control of the machines. There is also the possibility of utilising collision avoidance technology and automating the production loading process to remove personnel from the area.

5. *What design, caveability, operational and management risks are reduced using the new footprint and what new risks are introduced?*

There were many risks that were reduced through the redesign and reconfiguration of the production logic on the Extraction Level, including

- Implementation risks are reduced by simplifying the development layout and the number of profiles required to develop the level,
- The redefinition of where the work occurs, including the majority of production drilling to the Undercut Level, reduces the congestion and interaction risks on the Extraction Level,
- The increase in the fragmentation size which can be handled on the level, the reduction in the number of drawpoints and the truck loading strategies, including having a secondary loading point, reduces the operational risks associated with following the plan,
- The significant reduction in rehabilitation requirements reduces technical and operational risk associated with ore recovery, and
- The traffic management risks are reduced by utilising a one direction of travel through the footprint coupled with a reduction in the rehabilitation and secondary break requirements.

A couple of risks were identified as potentially increased, namely

- The ventilation of the level is more complex and requires the use of air moving fans in some situations, and
- the caveability risks are increased with the larger undercut blasts resulting in greater stress redistribution and potentially longer stand off times for seismicity.

Further to addressing the Research Questions, through the research completed during this thesis these key system requirements have been achieved and the comparison work completed to date on the Cube layout shows that it is:

- A more stable and resilient layout than the El Teniente despite utilising considerably larger Extraction Drives to allow for trucks on the level. The degree of drive closure for the Cube layout was less than half of that for a 30 x 24m El Teniente layout tested utilising Freeport DMLZ data. Keeping it well outside drive closure risk parameters ensuring that all drives and drawpoints are available for the life of the footprint.
- The flow simulations indicate that the 4-sided drawbell will recover the same amount of material as that expected from a 30 x 18m El Teniente layout. It must be noted that this size El Teniente layout is unlikely to be stable for the duration of the footprint's life so ore will ultimately be lost because of inaccessible drawpoints. The Cube design does not need to consider a potential recovery level as is the case for many El Teniente layouts below 1,200m.
- The productivity of the layout is considerably increased by segregating the load and haul functions and utilising equipment that is purpose built for each function. This strategy also ensures that each drawpoint on the level has essentially the same instantaneous production rate as the far drawpoints are serviced by additional trucks operating in a loop rather than being limited by the loader tramming speed.

- The consolidation of the trucks into the Extraction Level results in decoupling the location of the crusher from the footprint whilst also improving the fragment size that can pass freely through the system. Where currently ore passes are used when the crusher is off the footprint this results in a material change to the fragment size that interrupts the production flow. By loading straight into a truck, the critical particle size can be significantly increased to that which the crusher can accommodate or which the loader can pick up.
- Simplifying the geometry of the Extraction Level and the Undercut level allows for improved establishment rates and minimizes the number of development firings.
- The efficient production fleet results in a reduction of Operating cost and increases the likelihood of delivering the target tonnage from the level. The production rate set for the 350m by 200m footprint was 100,000tpd and this has been achieved. In comparison none of the El Teniente layout configurations were able to achieve the rate.
- The accelerated cave ramp up achieved through the efficient cave establishment results in significant financial benefit.

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