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Subika underground (SUG) production drilling evolution

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ABSTRACT

The Subika Underground Mine is part of Newmont Ghana Gold LTD's (Newmont) Ahafo South operations located in Kenyasi within the Asutifi North District of the Bono Region of Ghana. The Subika (SUG) gold deposit is hosted within a very strong and brittle rock mass. The deposit is relatively tabular in nature, averaging approximately 40m in width, 600m along strike and is open at depth. Early underground mining was by Sublevel open stoping with pillars, transitioning to a sub-level shrinkage (SLS) mining method at depth. The first mining level was a 20m sublevel which was longitudinal determined by Geotechnical evaluation. All other levels are 25m sublevel with a transverse method setup. There are between 40 to 50 drawpoints on a level as well as hanging wall development. The draw points are interspaced 15m from the centres. Production starts from the centre of the orebody and rings fired with chevron 3 rings lead-lag approach. There were initial challenges where slots designed to the levels above could not breakthrough after firing. This left bridges, which had production impact due to slashing of rings, re-slotting etc. The mine has gone through several iterations of drill designs to optimize the slot area of the mine most especially, with minimum design changes at drawpoints. The paper seeks to highlight the change of mining method from long hole open stope to SLS, the chevron mining method approach used to optimize drawpoint availability, production challenges with the drawpoints and slots, and remediations of these challenges.

1 INTRODUCTION

The Newmont Ahafo operation is located along a mineralized zone that extends approximately 70km in the Ahafo Region of Ghana, West Africa, approximately 307km northwest of Accra. It has been in operation since 2006, with production generated from a number of open pits. Figure 1 shows the Ahafo location relative to Accra and Kumasi. SUG is a down-dip extension of the Subika pit that has been in development since 2012. Underground production commenced in 2018 using a combination of Long Hole Open Stoping (LHOS) and Sublevel Open Stoping (SLOS), with stopes surrounded by permanent rib and sill pillars. Deeper areas are extracted using the Sublevel Shrinkage (SLS) approach, with a sill pillar to divide the two mining methods.

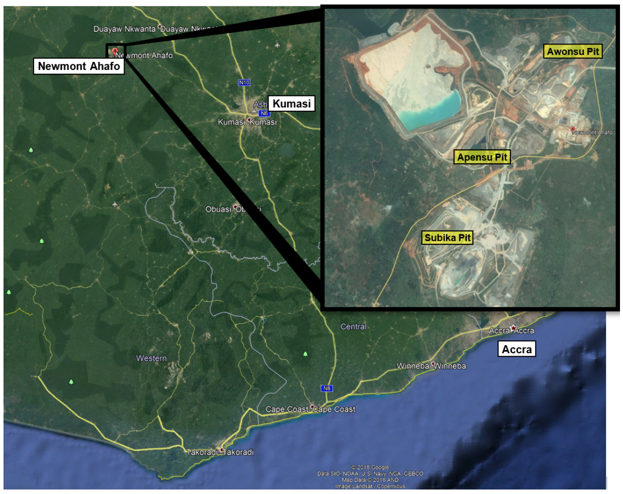

Figure 1 Aerial Photograph of Newmont Ahafo (Google Earth 2018).

2 MINE GEOLOGY

Subika is one of the largest of a group of gold deposits at Ahafo located in the Sefwi Belt as shown in Figure 2. It is developed in the hanging wall of the Kenyase Thrust Fault, but lies on a separate and parallel fracture zone to the fracture that hosts the Kenyase-style deposits. The main geologic unit of the Subika underground mine is granitoid. The gold mineralization at Subika is hosted within the Magic Fracture Zone (MFZ), a northeast trending southeast dipping (~045°/65 SE) zone of brittle fracture and veining ranging between 50 to 100m thickness. with mineralized lenses which vary in width from 2 to 20m.

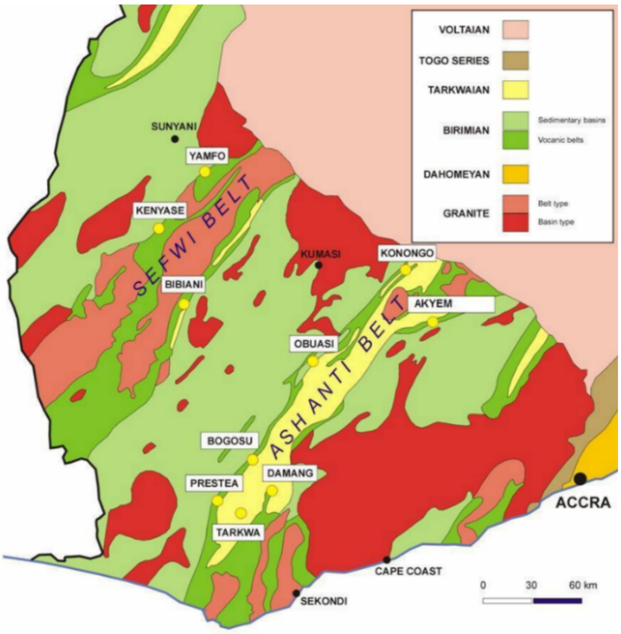

Figure 2 Geology of Southwest Ghana.

Five main structural zones, including the Victor Fault, Kaalbas Fault, Hatch Zone, Deep Fault and Denis Fault, are described, each exhibiting distinct characteristics and orientations within the Subika formation as shown in Figure 3.

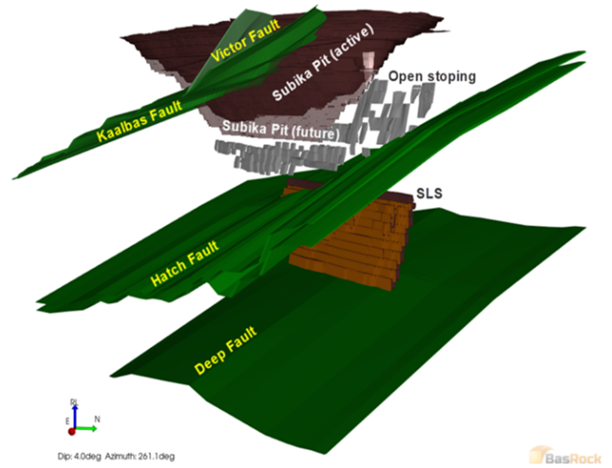

Figure 3 Structural Zones Relative to the Subika Pit and Underground Workings.

2.1 Rock mass Characteristics

The Subika deposit is in a sturdy granodiorite formation and lies in the hanging wall of the Kenyase Thrust. The orebody has a steep dip of about 70°, while major faults have a gentle angle of 20° to 30°. These faults are generally capable of causing local instabilities and are managed based on local conditions.

The Uniaxial Compressive Strength (UCS) is estimated at 154 MPa, based on a Weibull model fit using 113 sample test results from 2009 to 2018. Additionally, tests on 281 samples indicated a Young's Modulus of 73 GPa, with Poisson's Ratio set at 0.31, determined from a Weibull fit on the dataset. Stress measurements conducted at Ahafo using Acoustic Emission (AE) and Hollow Inclusion (HI) cell methods at different times revealed the following (GCMP, 2023):

i. Sigma 1 (σ_1) is sub-horizontal, roughly aligned from east to west and approximately three times larger than Sigma 3.

ii. Sigma 2 (σ_2) is similar in magnitude to Sigma 3.

iii. Sigma 3 (σ_3) is sub-vertical and roughly equal to the overburden stress.

3 MINE DESIGN

3.1 Mining History

The underground study of the Subika orebody commenced in 2005 with full scale mining operations commencing in January 2006 as an open pit.

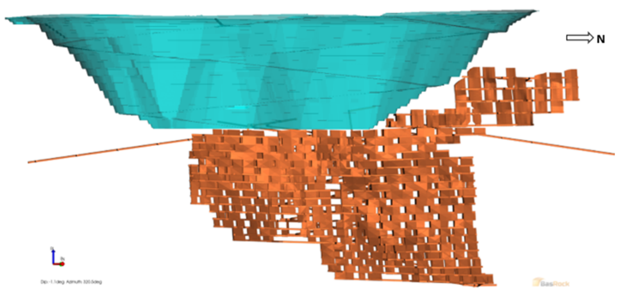

Figure 4 Initial business Case for the SUG project with Phase 4 pit design.

The SUG project, as shown in Figure 4 above, was intended to become an underground mine to access the gold ore deposit beneath the Subika pit, separated by a crown pillar below the ultimate Phase 4 open pit layback scheduled to be completed in 2025. Underground mining commenced in May 2017, using a combination of Long Hole Open Stoping (LHOS) and Sub-Level Open Stoping (SLOS), with the first production ore in 2018.

3.2 Change in Mining Method

In response to geotechnical challenges i.e. the adverse in-situ stress conditions and variations in the rockmass quality experienced in few months into production, a geotechnical review was conducted in April 2018. This revealed the aggressive nature of the initial geotechnical guidance which had permitted high extraction ratios, slender pillars and no consideration for backfilling opened voids.

Revision of the assumptions to allow reduced extraction ratios and backfilling of open stopes with waste rock resulted in the original business plan for SUG no longer being viable in terms of using the LHOS and SLOS mining methods at depth. A cross-functional team consisting of Newmont's geotechnical team and external subject matter experts was established to identify an alternative mining method for SUG and address the near-term impacts to the operation.

The mining options analysis confirmed that changing the mining method to SLS addressed the geotechnical constraints while providing long-term economic value. The new business case is shown in Figure 5. In order to ensure seamless mining operations, a 50m thick sill pillar (750 - 700mRL) was left to separate the upper stoping area (SLOS and LHOS mining blocks) from the proposed SLS mining block.

The illustrated roadmap for the SUG Project is depicted in Figure 6.

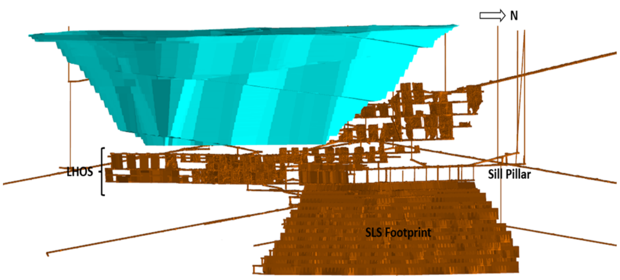

Figure 5 Final Approved business case for the SUG project with Phase 4 pit design.

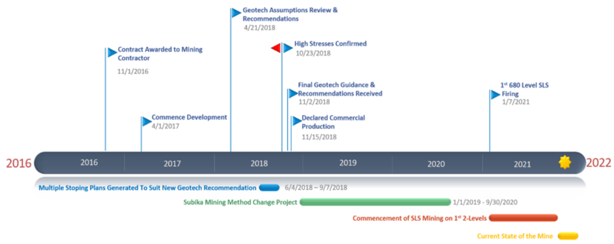

Figure 6 SUG Project Roadmap.

3.3 Mining Method

Typically, the SLS mining method utilizes a production front resembling that of a sublevel cave (SLC). However, it distinguishes itself by incorporating unconsolidated fill (comprising waste or low-grade rock) within the cave zone, on top the broken ore which serves to stabilize the surrounding rockmass and mitigate the risk of uncontrolled cave-ins of the overlying strata, as illustrated in Figure 7 (Mackay et al., 2014).

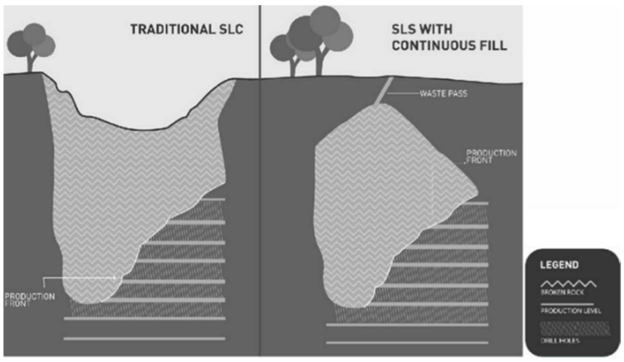

Figure 7 Sublevel Cave (Showing Caving of Overlying Strata) versus Sublevel Shrinkage with Continuous Fill (After Mackay et al, 2014).

Brand and Haider (2023) adds that the method follows a top-down mining sequence, with production drifts oriented either transversely or longitudinally within the orebody, enabling fan drilling and blasting operations to be conducted for ore extraction. During the extraction process, backfill is introduced from the top via fill passes to serve as confinement to the cave walls, thereby maintaining the integrity of the sill pillar as illustrated in Figure 8. Caving commenced beneath the sill pillar at the 680mRL, with plans for progression down to the 410mRL level.

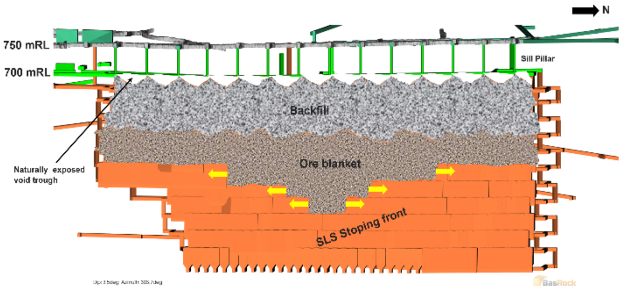

Figure 8 Schematics of the SUG's SLS.

The SLS sub-levels are 25m spaced from floor to floor and oriented along the NE-SW orientation of the deposit. Transverse crosscuts or drawpoints are 5.0m wide and 5.0m high placed at 15m centre to centre spacing, thus a 10m pillar remains between each drawpoint. A drive is located sub-parallel to the hangingwall ore boundary to serve as the slot extraction on each level. These slots are located to link with the upper level mostly, however some are placed stepped out to the hangingwall (step-out) where the grade boundary moves further into the footwall or hangingwall. Step-ins are formed where the lower level slot extent is laterally inside the ring footprint of the level above. A typical level layout is provided in Figure 9 below.

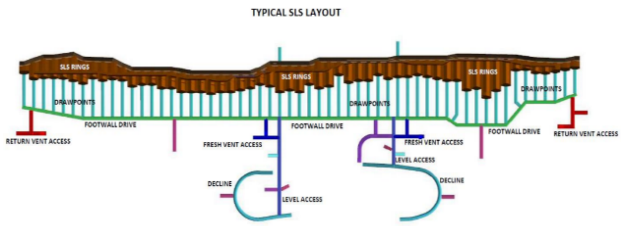

Figure 9 Plan view of a general level layout.

In addition, it is important to mention that the longitudinal approach was utilized in mining the first level at the start of the SLS mining, 680mRL as shown in Figure 10 and Figure 11. This was based on economic analysis conducted on the 18m maximum width stopes sizes recommended by the Geotechnical team. According to SRK Consulting (2019), this limits the sill pillar undercut width to a hydraulic radius (HR) of 8.8m which will provide a stable with support conditions for the whole strike length of the sill pillar undercut.

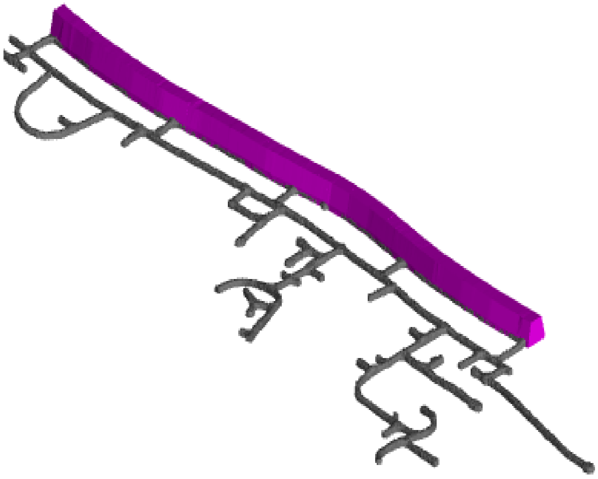

Figure 10 Longitudinal mining front (680 L).

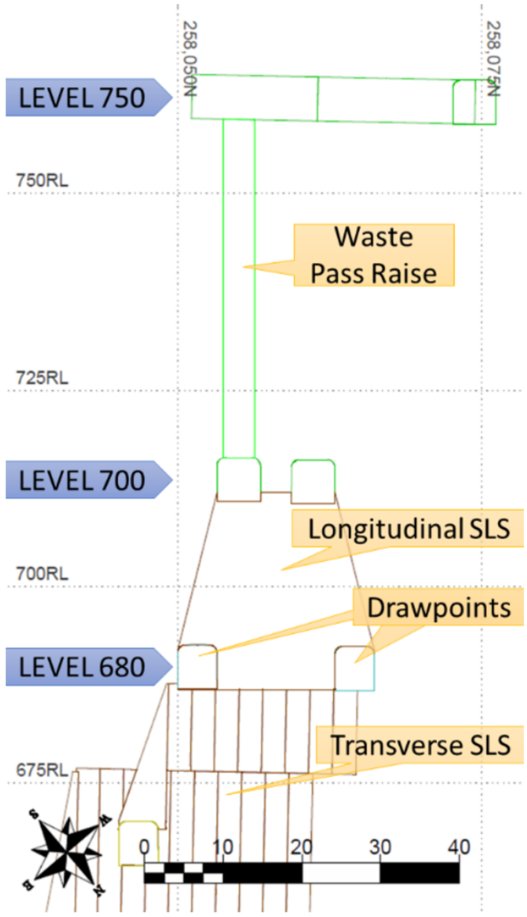

Figure 11 **Cross section showing the waste rock pass, upper longitudinal SLS and lower transverse SLS.**

Figure 12 shows a vertical section of the general mining sequence of a single stope at SUG. Initially the footwall drive is developed, followed by the drawpoints and slot drives. Mining then begins with slotting activities (slot production drilling, slot charging, bogging) starting from the central drawpoint, advancing along the strike of the orebody. Drawpoint production drilling, charging, and bogging is then finalized to the planned tonnage following a center-out retreat fashion. This sequence is repeated towards the footwall drive until all the rings in the drawpoints are completed as shown in Figure 13, thereby allowing for pre-drilling and pre-charging of production rings.

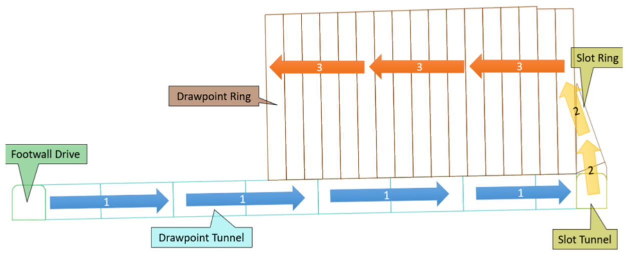

Figure 12 **General Mining Sequence (Section View).**

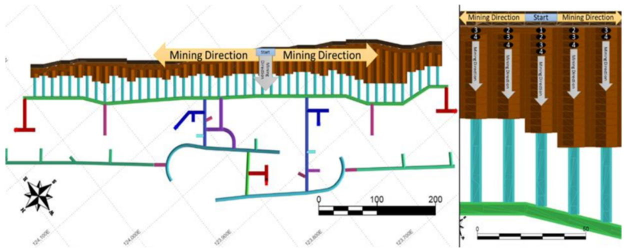

Figure 13 **General Sequence and mining direction for production rings on a level.**

The slot and first two rings in each drawpoint on each production level is mined out using an open stope concept because they do not break through into the cave after firing. Referred to as "pocket rings tonnes", this approach aims to maximize production on the level.

4 PRODUCTION CHALLENGES WITH DRAWPOINT AND SLOT RINGS AND THEIR REMEDIATION

Since 2019, the SLS mining method has seen the application of various production drill design options, with modifications made in response to encountered challenges such as bridging after firing in slots, incomplete slot heights post-firing, ring slashing due to bridging, back breaks after firing and bogging, and safety concerns during charging. These challenges have notably impacted production efficiency.

The chronological evolution of these design options implemented since the inception of the SLS mining method at SUG is detailed below. This progression of options has enabled the team to gain insights into on-site challenges, thereby facilitating the implementation of remedial measures with each modification.

4.1 Drill Design Option 1

In this drilling option, the slot was designed to break through into the upper level as shown in Figure 14. The ring burden was 2.8m and forward dumped 10° from the vertical.

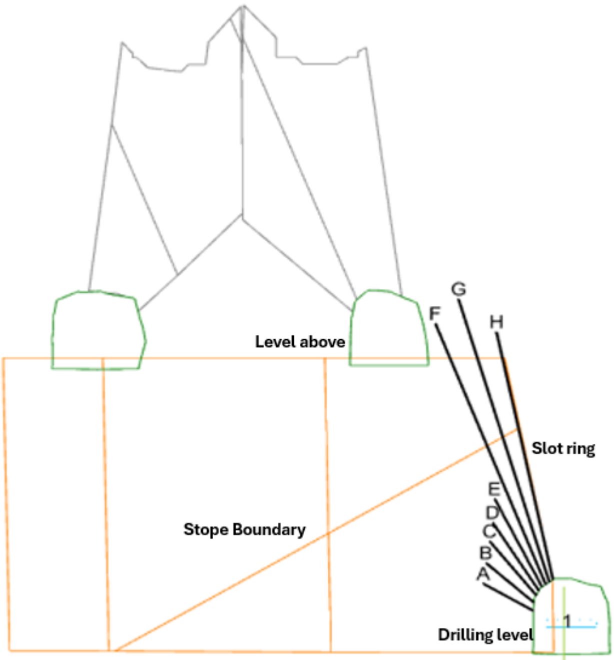

Figure 14 Design Option 1.

The foremost challenges encountered during this phase were as follows:

i. Difficulty in retaining the collars of subsequent rings awaiting firing within the slot, primarily due to the inflow of fill cave material post-firing.

ii. Excessive bogging of rings in attempts to recover the collars of the next uncharged rings, leading to inefficiencies.

iii. Reduction in slot height, necessitating re-slotting and consequently impeding production rates.

In response to these challenges, the design underwent modification, leading to the development of Option 2, as outlined below.

4.2 Drill Design Option 2

The slot hole lengths were adjusted to prevent breakthrough into the level above, maintaining the 2.8m ring burden. Additionally, two easer holes were drilled from the same plane in front of each slot ring, with a forward dump of 12°, while the main slot rings were dumped forward at a 10° angle. The slot ring comprised three holes with varying lengths and dips, whereas the easer ring consisted of two holes, also with differing lengths and dips, positioned between the centers of the three main holes in each slot ring, as depicted in Figure 15.

However, a significant challenge arose as the designed slot height was not achieved due to a minimum 3m - 3.5m vertical height difference allowed between holes in the slot rings. Subsequently cavity monitoring scans taken from various slot cavities were applied to revise the drill design, leading to the development of Option 3.

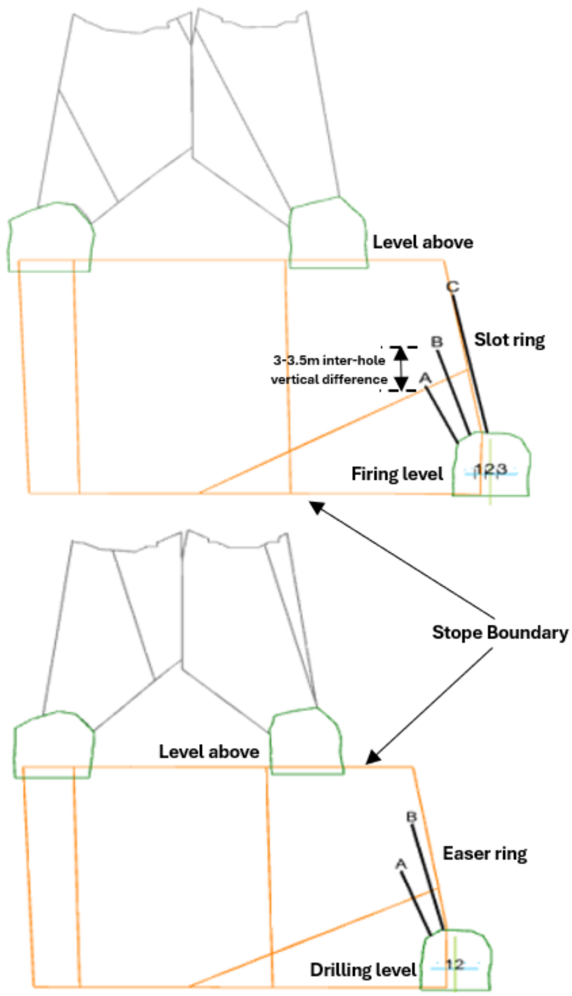

Figure 15 Design Option 2.

4.3 Drill Design Option 3

In this design option, the length of the individual slot holes was slightly increased from that of Option 2. Additionally, the burden of the slot was reduced from 2.8m to 2.0m, taking into account the stope shape boundaries and the hanging wall contact. Like option 2, the slot ring consisted of three holes with varying lengths and dips but ensuring a vertical height difference within 2m to 2.5m from hole to hole, as illustrated in Figure 16. Unlike Option 2, easers were not employed in this option.

While this design demonstrated notable improvement over Options 1 and 2, it still encountered challenges with the formation of toe and collar bridges after firing, necessitating its modification.

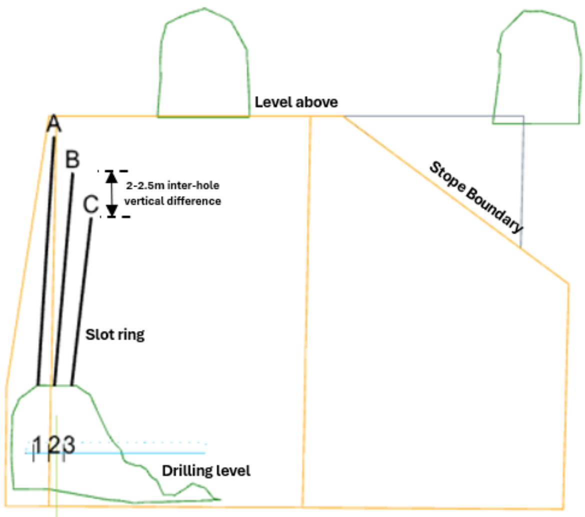

Figure 16 Design Option 3.

4.4 Drill Design Option 4

In this option, the slot drilling maintained the three holes per ring as in the previous design, while easer rings were introduced with one hole drilled 0.4m in front of the main rings as shown in Figure 17.

Additionally, a design change to the draw point rings was implemented, where the first three rings, as depicted in Figure 18, were fired simultaneously (mass firing) due to being drilled on the same plane (stand-up rings), with their dump angles adjusted to a 10° dump on the 3rd ring.

Challenges included the loss of collars of the initial draw point rings, necessitating recovery drilling and causing production delays. Despite these challenges, this design option exhibited notable improvements compared to previous options, reducing the occurrence of bridges within the slots.

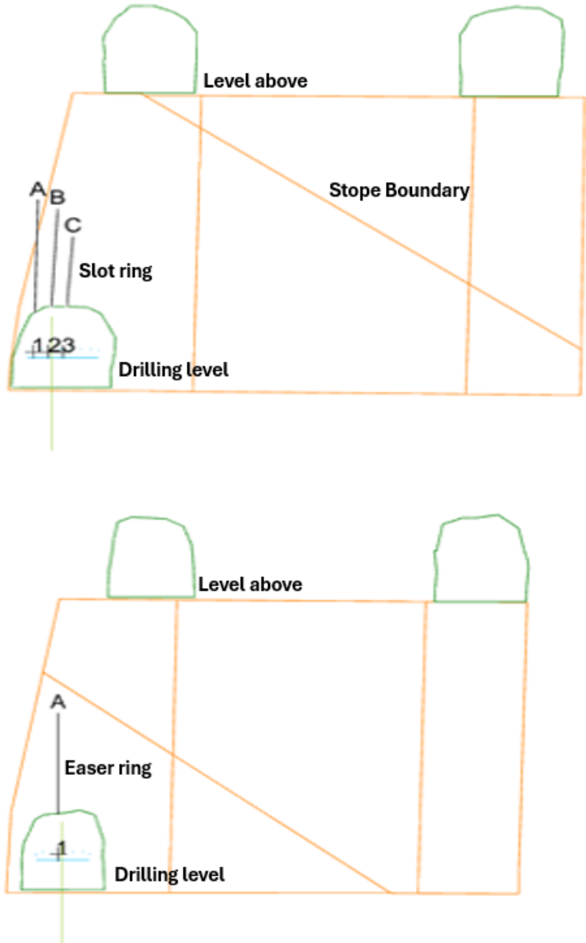

Figure 17 Design Option 4.

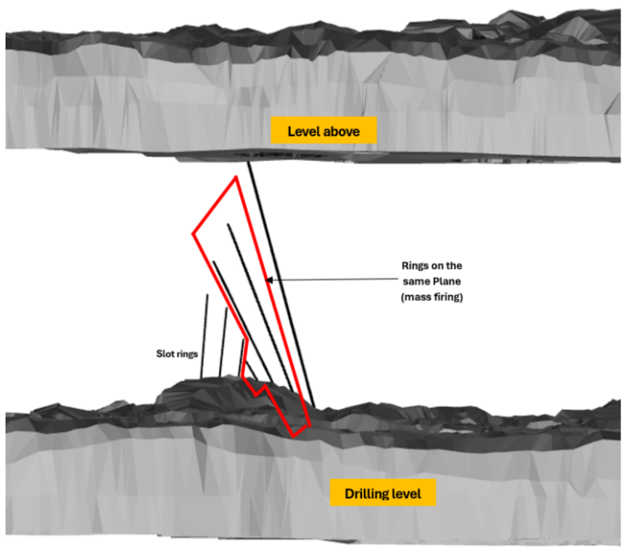

Figure 18 Slot relation to the initial drawpoint rings.

4.5 Drill Design Option 5

In response to the collar loss issues observed in Option 4, a redesign of the draw point rings was undertaken to mitigate the risk of mass firing the first three rings in the draw point. The slot drilling was executed following the dice 5 concept, consisting of two holes per ring and one easer ring drilled 0.4 meters ahead of the main slot ring (see Figure 19).

The 2m burden was maintained in this option, with the drawpoint rings modified to have two or three individual rings before the three dumped rings on the same plane as shown in Figure 20. While this option did not exhibit any major flaws, the slot hole lengths were increased to mitigate the height loss challenges experienced post-firing.

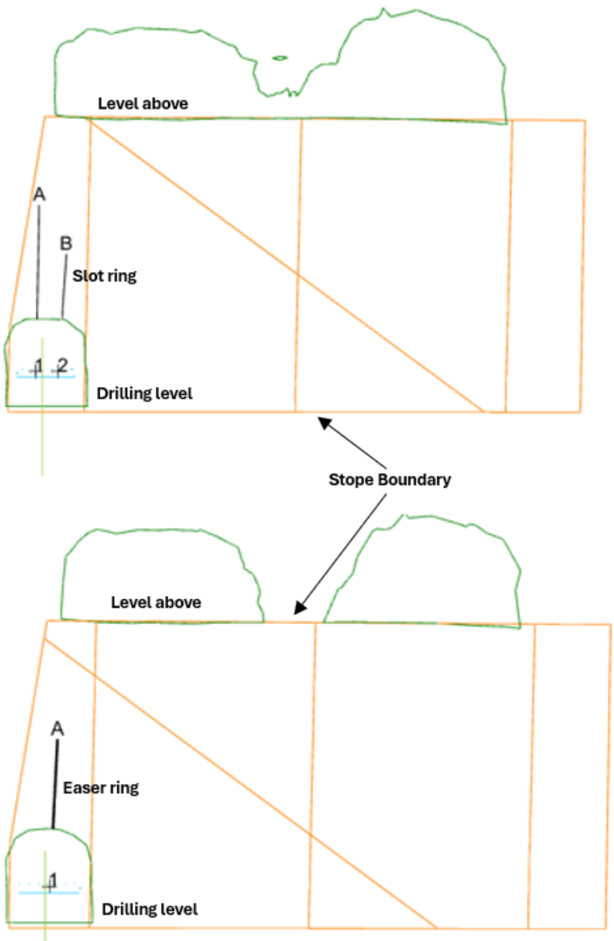

Figure 19 Design Option 5.

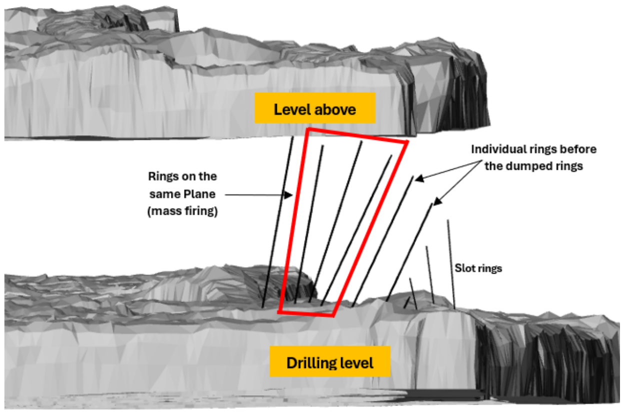

Figure 20 Slot relation to the initial drawpoint rings.

4.6 Drill Design Option 6

Addressing the height losses observed in Option 5, an additional 2m was incorporated into the lengths of the slot ring holes and easer holes. The two holes in the main ring averaged 6m to 10m in length, while the easer ring measured 8m. This modification proved to be successful in addressing the height loss issues encountered in Option 5. Figure 21 shows a sample drill design under this option.

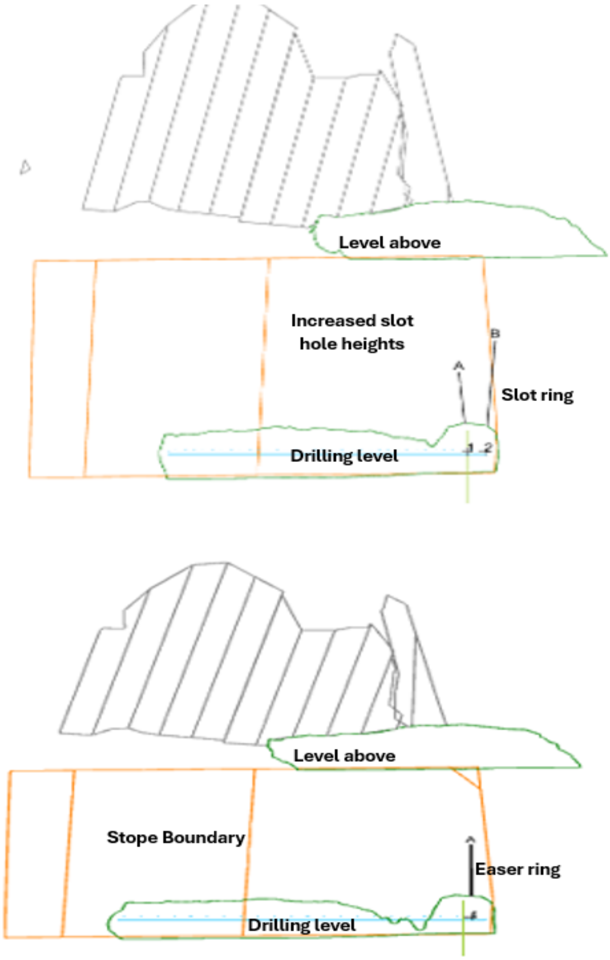

Figure 21 Design Option 6.

4.7 Drill Design Option 7

Design option 7, an advancement of Option 6, introduced an increase in the number of stand-up rings from three to four as shown in Figure 22. This adjustment aimed to mitigate the toe burdens arising from the utilization of higher dump degrees necessitated by the alteration in slot height. This option is currently implemented in areas of the mine devoid of island pillars.

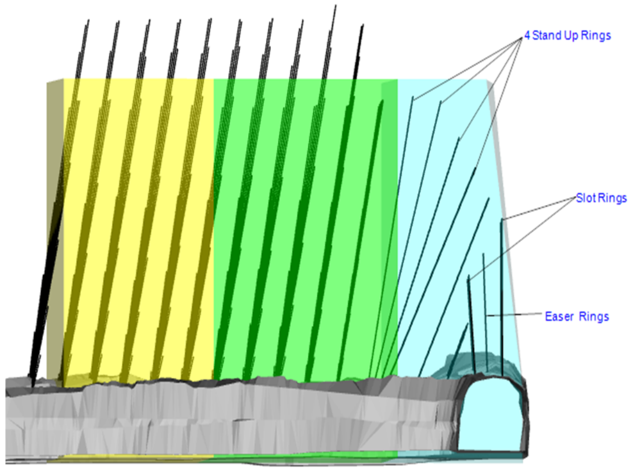

Figure 22 Design Option 7 on 610mRL.

5 DRAWPOINT RING DESIGN OPTIMIZATION

Initially, the drawpoint rings were designed with a burden of 2.8m dumped forward at 10º to the vertical. However, this was subsequently reassessed, and the burden adjusted to 2.5m dumped at a 10º angle. This modification was influenced by feedback from the mining contractor (Underground Mining Alliance) and on-site studies conducted by subject matter experts. A single pivot was used for the 2.8m burden, whereas the current practice involves the use of three pivots for the 2.5m burden. This change decreases the total drill meters and minimizes blast impact at the stope brow. As exemplified by the drill designs depicted in Figures 23 and 24, the adoption of a 2.5m burden design resulted in a reduction of total drill meters from an average of 180.3m to 148.6m (18%), indicating a significant improvement in efficiency and resource utilization.

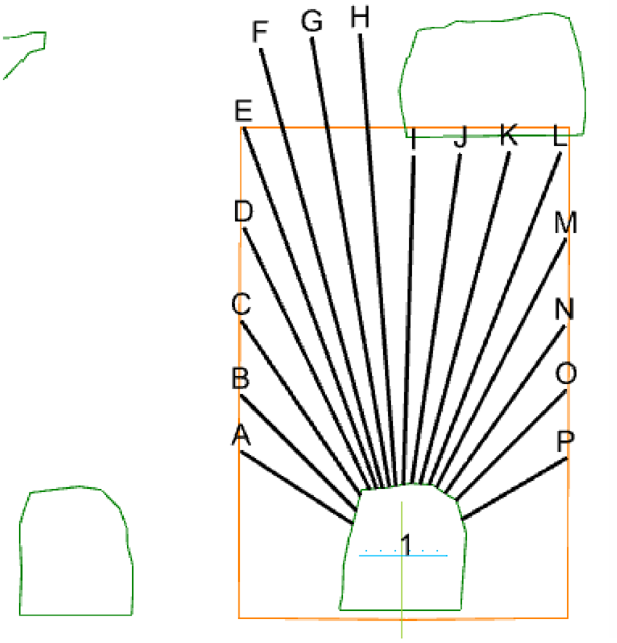

Figure 23 A 2.8m burden ring with one pivot.

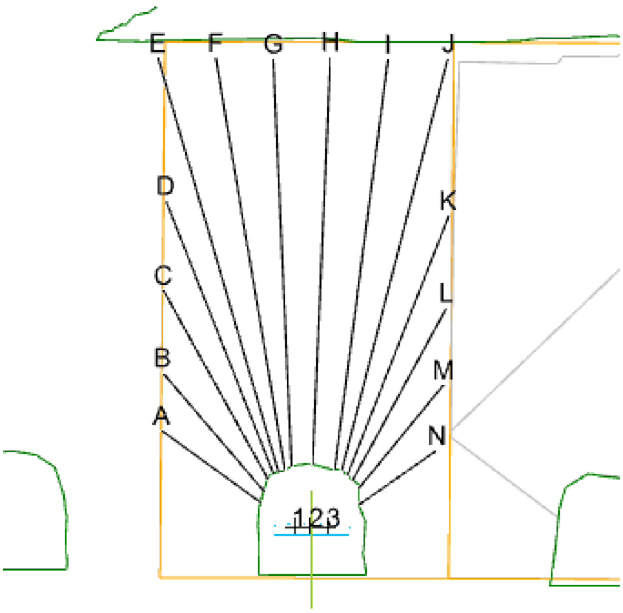

Figure 24 A 2.5m burden ring with three pivots.

5.1 Island Pillar Drilling

The concept of the island pillars (see Figure 25) in the Subika SLS mine design seeks to reduce the ground support elements used when the draw points are designed to breakthrough into the slot drive, improve ventilation on the levels and allow the slot drive to be fired well in advance of the breakthrough drawpoints to create a stress halo between the footwall and hanging wall sides of the mine. This aims to minimize seismic activity during production blasting.

Due to the presence of these island pillars, it has become imperative to revise the ore production ring designs and firing strategy. This revision entails firing the island pillar development simultaneously with the first 3 rings in the drawpoint, as illustrated in Figure 26.

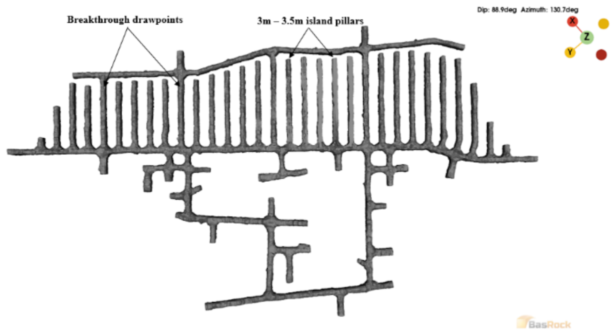

Figure 25 Island Pillar Concept at SUG (560 mRL).

This drill and blast design and sequence aims to ensure the safe breakthrough of the pillar (3m-4m) left prior to the slot breakthrough, thereby enhancing operational efficiency. This facilitates multiple draw points in production simultaneously, as slot firings become independent of drawpoint firings.

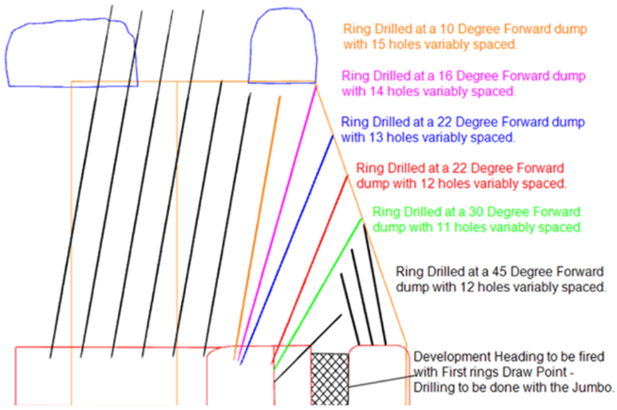

Figure 26 Drilling and Firing Sequence in Drawpoints Island Pillar.

Additionally, this approach aims to minimize, if not eliminate, the firing of multiple slot rings, historically associated with triggering seismicity. The island pillar drill design is derived from a modification of design Option 7 and is currently utilized in areas on the mine where island pillars are present.

5.2 W-Straps

To address back breaks and production ring losses experienced in the upper SLS levels, SUG implemented the installation of W-straps between production rings in the drawpoints. While there may be occasional production delays due to W-strap installation, their implementation has notably diminished the loss of production ring collars and reduced slash drilling costs.

5.3 Concurrent Firing

The simultaneous firing of rings in adjacent drawpoints aims to enhance blasted stocks and productivity. However, this firing method is currently in the trial stage, as it is accompanied by higher ground vibration magnitudes. Geotechnical data collection and assessment are ongoing to evaluate its effectiveness and mitigate potential risks.

5.4 Charge and Drilling Audit (QAQC Activities)

The objective of QAQC activities at SUG is to monitor charging and drilling practices and provide recommendations as needed. The audit primarily focuses on factors such as the quantity of explosive loaded into each hole, charging of correct blast holes, density checks, drilling accuracy, and other relevant parameters. This process has significantly improved blasting practices at SUG.

6 THE CHEVRON MINING APPROACH

A chevron mining layout, as shown in Figure 27, is a common stress control technique adopted at SUG during stoping operations. According to Bawden (2023), this design pushes stress front towards the solid abutments, eliminating the risk of pillar bursts and providing for more uniform stress conditions on each level.

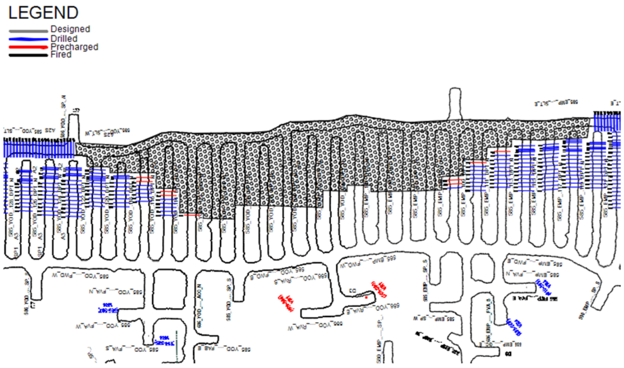

Figure 27 Active Chevron Layout (585 mRL).

Since adoption at SUG, the method has helped improve blasted and drilled stocks underground as illustrated in Figure 28, reduced rock stress concentrations, and minimized ring losses resulting from flow of material from the upper level after breakthrough.

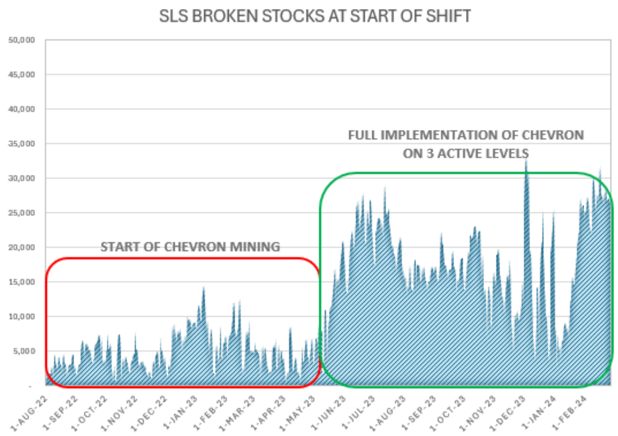

Figure 28 SLS Tonnes at Start of Shift Chart.

From Figure 28, SUG realized up to a 100% increase in broken tonnes at start of shifts following a complete integration of the Chevron mining sequence on three active levels. This notable increase can be attributed to the creation of numerous drawpoints facilitating efficient bogging operations during shifts.

To ensure long term sustainability of SUG throughout its operational lifespan and beyond, adherence to well defined strategies for cave draw, drilling and ring firing is paramount. These strategies, outlined in the mine's "SLS General Rules (Drilling & Firing)" document, serve to elaborate on the overarching principles governing the SLS cave management.

Generally a 3 ring lead-lag for ring firing and production drilling is strictly adopted, with exceptions accommodated through an existing Triggered Action Response Plan (TARP) system for operational reasons. Sections 6.1 to 6.4 summarize these rules across all production activities.

6.1 The Chevron Drilling Rules

A 3-ring lead-lag rule is implemented at SUG, following the chevron mining pattern. The process entails the following steps:

i. For a typical start of a level, up to 11 complete slots (covering 11 drawpoints) in the hanging wall slot drive averaging 2,000m is drilled, starting from the center of the orebody towards the West and East directions.

ii. Subsequently, the first 5-6 drawpoint rings, averaging 850 meters, are drilled across the 11 drawpoints.

iii. The initial 5-6 drawpoint rings are mined as open stopes since the rings do not break into the level above. This is aimed at generating initial tonnes on the level before the rings in the central drawpoint starts production, breaking into the level above.

iv. Where the initial drawpoint rings sit directly underneath the drive on the upper level, the drawpoint rings are not mined as an open stope.

The slot drilling and initial drawpoint ring utilizes the design approach depicted in Figure 29, aiming to establish a natural trough before accessing the cave on the upper level. This strategy is implemented to facilitate favorable backfill outcomes.

Figure 29 Active Chevron Layout (585 mRL).

6.2 The Chevron Firing Rules

i. On a level, the firing commences from the slot in the center of the orebody to open the width of the orebody along the strike. The slot is treated as open stope; hence bogging is free.

ii. Apart from the central drawpoint which could be taken in several shots, all other slot rings are fired in two shots. The first shot is made up of two slot rings with easers and the second, four to six slot rings with easers (currently being revised).

iii. The second shot is initiated simultaneously with the first production ring in the drawpoint to prevent collar loses during the intersection firing. These two shots open the full width of the draw point.

   a. Due to the initial project scope, concentrating on one to two levels at a time, it will take the mine some time to get to a lead lag strategy vertically as drawpoints would be advanced such that there is no risk of undercutting from the lower levels.

   b. When the mine gets to mining three active levels and beyond, there will be a lead lag rule of the level above being 25m ahead of the level below in the same draw point to ensure there is no undercut, better cave flow and reduce the risk of potential boulders reporting at the lower level drawpoint.

6.3 The Chevron Pre-charging Rules

i. While SUG has approval to pre-charge up to five rings, current drilling and firing strategy does not mandate pre-charging all five rings.

ii. The minimum Site requirement for an active drawpoint is two pre-charged rings, with any additional rings considered as an opportunity. This approach ensures that energy is directed where charging is necessary to build up broken stock inventory, particularly for the initial few ring tonnes ("pocket tonnes") in the drawpoints, which is usually treated as open stope tonnes.

iii. Investigation into the implementation of Orica's WebGen dets for pre-charging is currently underway for Subika.

6.4 The Chevron Ore Rill Rules

i. Typically, the tonnes from the immediately fired ring will naturally fill the floor, extending up to the next two rings after the fired ring.

ii. For the purposes of keeping buffer drill stock to conform with the pre-charge procedure, ring buffer is set at three rings (1 pre-charge ring = 2.5m burden, 2 rings =5m burden).

6.5 Drilling In Active Draw Point

i. The solo horseshoe fits and is able to set and drill with a 3-ring rill buffer.

7 CONCLUSION

In conclusion, mining operations entail numerous challenges necessitating ongoing engagement and enhancement to boost productivity while prioritizing safety. At SUG, the challenges associated with drill and blast activities have been successfully addressed over time. Significant advancements in production drill designs, informed by operational challenges, as well as innovations such as the utilization of island pillars, adoption of chevron mining, implementation of QAQC activities, and the introduction of strapping between rings have been pivotal in enhancing ore generation. These initiatives collectively underscore the continuous commitment to improvement and excellence in mining practices at SUG.

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