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School of Mining Engineering



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

INVESTIGATION OF LONG-HOLE STOPE PERFORMANCE AT SOUTH DEEP GOLD MINE.

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, May 2024

DECLARATION

I declare that this report is my own, unaided work. I have read the University Policy on Plagiarism and hereby confirm that no plagiarism exists in this report. I also confirm that there is no copying nor is there any copyright infringement. I willingly submit to any investigation in this regard by the School of Mining Engineering and I undertake to abide by the decision of any such investigation.



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ABSTRACT

South Deep Gold Mine is located 45km south west of Johannesburg within the gold-rich Witwatersrand Basin. The reefs at the mine occur within an economically significant stratigraphic bundle containing Ventersdorp Contact Reef (VCR) and Upper Elsburg conglomerate units. Long-hole stopping (LHS) is the primary method of mining and accounts for over 60% of the gold produced at the mine.

It is, therefore, critical that the stopes meet the required production output for the designed mine lifespan at efficient stope turnaround times. However, mine data suggests that ore production from LHS has been erratic and has significantly affected the mine's ability to produce to its installed capacity.

The reduction in productivity and utilization is an area requiring research and this project investigated LHS performance at the mine to understand factors that influence stope turnaround time. Three research questions guided the study intending to improve LHS performance:

- What is the influence of geological environments on LHS performance;
- How do design aspects at South Deep affect LHS performance; and
- How do current drilling and blasting practices affect LHS performance?

To answer the research questions, the research adopted a stepwise process of categorising mining environments, analysing stope data files on Deswik software, developing predictive models on Python and MS Excel, informing excavation design, and finally reviewing drilling and blasting practices at the mine. These steps helped in leveraging the intersection that exists between geological environments, technical design aspects as well as operating tactics at the mine.

The findings from the research questions led to the emergence of two themes. The first theme corresponding to the influence of geological environments and design aspects relates to the application of engineering principles in the mining environment, within the jurisdiction of the mining engineer / mine planner. The second theme, corresponding to drilling and blasting practices, relates to operational excellence, within the jurisdiction of the miner. The success of LHS performance hinges on the interplay and balance of these two themes.

The major findings of the research indicated that deviation from set standards and malfunctioning components compromised drilling accuracy while wrongly charged holes (over-charged/under-charged) compromised blasting efficiency. They further showed that conventional and de-stress cut environment stopes were the most susceptible to over-break. Severe over-break was found on Secondary and Sequential stopes, predominantly on hanging walls and footwalls. Hanging walls and footwalls with hydraulic radius (HR) values above 6.0 (mine standard) also showed high susceptibility to over-break.

In the process of analysing the results, the research developed a multi-variate model to predict the behaviour of the relationship between LHS performance and HR. It also created a matrix that informs how the mine may manage over-break. The research concluded by giving a set of recommendations for improving LHS performance, the chief of which emphasised the importance of strict supervision of drilling and blasting practices underground, measuring drilling against quality and quantity metrics as well as aiming for designing stopes with HR values below 6.0. It further recommended the adoption of the stoping scenario matrix developed, the improvement of the integrity of backfilling as well as the automation of the drilling and charging processes.

DEDICATION

To me.

This one is for me.

For leaving the comfort zone and challenging for something bigger than myself.

For having a will power greater than all voices of doubt and fear.

Most importantly, for belief in my **“I can, I will”** dictum.

ACKNOWLEDGMENTS

I would like to extend my deep appreciation to Gold Fields for funding me and allowing me to conduct my research at their mine. I am grateful to members of the technical services department at South Deep mine for their various contributions towards ensuring the success of the project.

Special appreciation goes to Nkhangweni Ratshitaka, my mine contact person and supervisor for walking me through the journey and intervening during trying times. I further express my gratitude to Professor Gordon L. Smith, my academic supervisor for his patience and guidance from the conceptualization of the project to its completion.

Lastly, I thank the Almighty God, without whom all of this would not have been possible.

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LIST OF ACRONYMS

Acronym	Full Name / Description
CAF	Cemented Aggregate Fill
CHF	Cemented Hydraulic Fill
CMS	Cavity Monitoring System
CoD	Coefficient of Determination
CPF	Cemented Paste Fill
CRF	Cemented Rock Fill
CV	Conventional
DC	De-stress Cut
ECB	Elsburg Individual ‘C’ Bottom Band Conglomerate
ECBA	Elsburg Individual ‘C’ Basal Band Conglomerate
ECBAQ	Elsburg Individual ‘C’ Basal Band Quartzite
ECBQ	Elsburg Individual ‘C’ Bottom Band Quartzite
ECMC	Elsburg Individual ‘C’ Middle Band Conglomerate
ECMQ	Elsburg Individual ‘C’ Middle Band Quartzite
ECT	Elsburg Individual ‘C’ Top Band Conglomerate
ED	Elsburg Individual ‘D’ Band Quartzite
ELOS	Equivalent Linear Over-break/Slough
FW	Footwall
HF	Hydraulic Fill
HR	Hydraulic Radius
HW	Hanging wall
LHS	Long-hole Stope
LV	Lava
MAC	Modderfontein ‘A’ Band Conglomerate

MAD	Main Access Drive
MAD	Modderfontein ‘A’ Band Degenerate Quartzite
MAPE	Mean Absolute Percentage Error
MBB	Modderfontein ‘B’ Band Bottom Conglomerate
MBT	Modderfontein ‘B’ Band Top Conglomerate
MedAE	Median of Absolute Errors
MIB	Modderfontein Intermediate Bottom Band Conglomerate
MIQ	Modderfontein Intermediate Quartzite Band
MIT	Modderfontein Intermediate Top Band Conglomerate
O/B	Over-break
OD	Open Development
OS	Open Stope
QAQC	Quality Assurance and Quality Control
RQD	Rock Quality Designation
SD	Stope Drive
SL	Solid Ground
SRF	Stress Reduction Factor
U/B	Under-break
UG	Underground
URF	Uncemented Rock Fill
VCR	Ventersdorp Contact Reef
WAGM	Western Areas Gold Mine

1 INTRODUCTION

This opening chapter provides an overview of the South Deep Gold Mine as well as the background of the research. It further introduces the research approach taken and lays out the structure of the research report.

1.1 Mine Background

1.1.1 Timeline and history

The establishment known today as the South Deep Gold Mine traces its roots back to the middle of the 20th century (Gold Fields, 2022b). In 1950, Ventersdorp Contact Reef (VCR) and Upper Elsburg conglomerates were discovered in Westonaria and prospecting began in that area.

According to the history of the mine (Gold Fields, 2022b), the Elsburg Gold Mining Company was formed in 1965 and ten years later would be consolidated into Western Areas Gold Mining (WAGM). Further exploration led to the realization that the orebody had the potential for sustaining mechanised mining in 1980. South Deep Exploration was formed to raise more funds for exploration in 1990 and would merge with WAGM five years later to commence shaft sinking.

In 1999, a Placer Dome/Western Areas joint venture was created and in the following year its name changed to South Deep Gold Mine (Gold Fields, 2022b). The sinking of the main shaft was completed in 2002, together with the commissioning of a new gold plant. A further two years down the line, the twin shaft system was commissioned.

Barrick acquired Placer Dome in 2006 and within the same year, sold its 50% stake to Gold Fields. Gold Fields gained full shareholding of Western Areas, and in the process assumed full ownership of South Deep Gold Mine in 2007. The change of ownership saw the new owners initiating a R4.3 billion mine upgrade investment program that among other things ushered in the cessation of all conventional mining practices in 2008 (Gold Fields, 2022b).

In 2009, the mine started low-profile de-stress mining to deal with stress-related problems at depth. This would later be changed to high-profile de-stressing in 2015, reducing the corridor spans and numbers. Gold Fields implemented a rebase plan worth R2.3 billion to assist the South Deep Gold Mine operation in reaching its full potential in 2016. The mine then introduced a new approach to reduce mining areas, lower overhead costs, improve fleet availability and accelerate backfill placement in 2018 (Gold Fields, 2022b). From 2019 to date, the company has been operating profitably.

1.1.2 Location

South Deep Gold Mine is situated approximately 45 km south-west of Johannesburg, the commercial capital of South Africa, and about 20 km south of Randfontein. The mine lies within the West Witwatersrand region, occupying 4, 232 ha of land with the longest and widest stretches extending to 9.5 km north-south and 4.5 km east-west respectively. Figures 1-1, 1-2 and 1-3 sequentially correspond to the location of the mine concerning surrounding towns, and neighboring mines as well as the underground (UG) plan of the mining area as at the end of the year 2020.

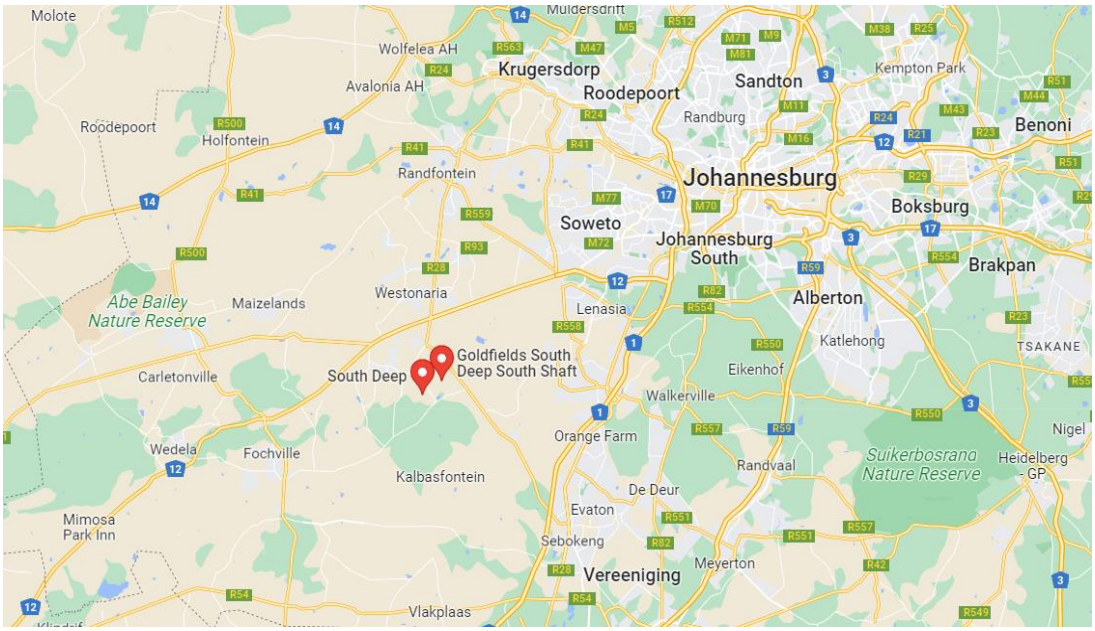


Figure 1-1: Location of South Deep Gold Mine concerning surrounding towns (Source: Google Maps)

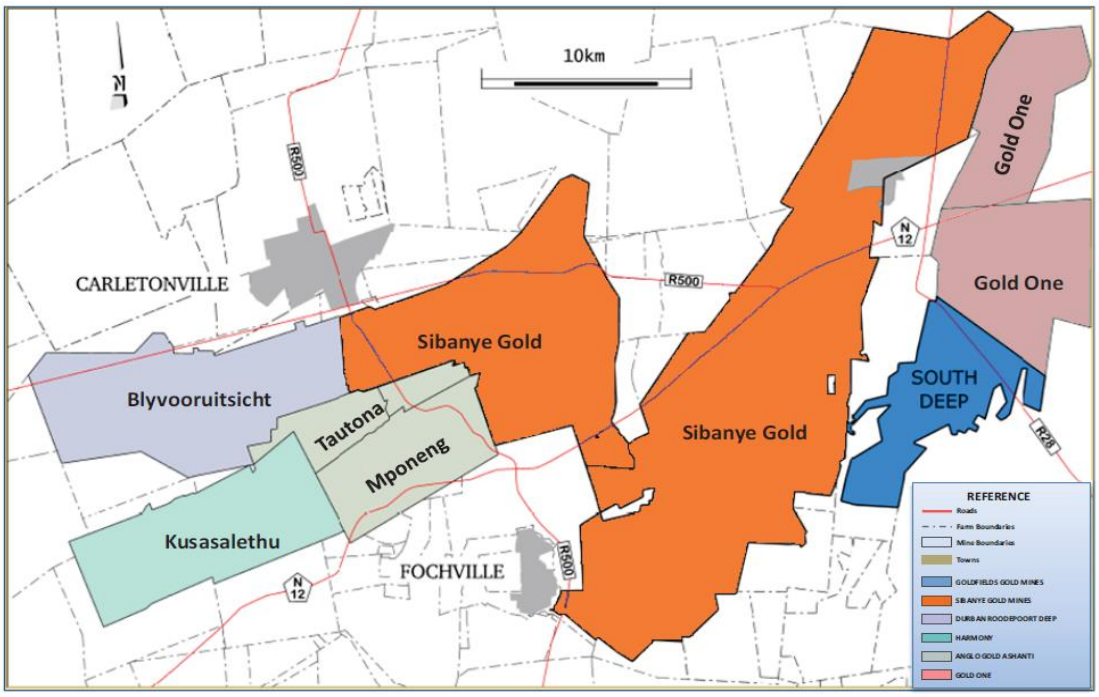


Figure 1-2: Location of South Deep concerning neighboring mines (Gold Fields, 2013)

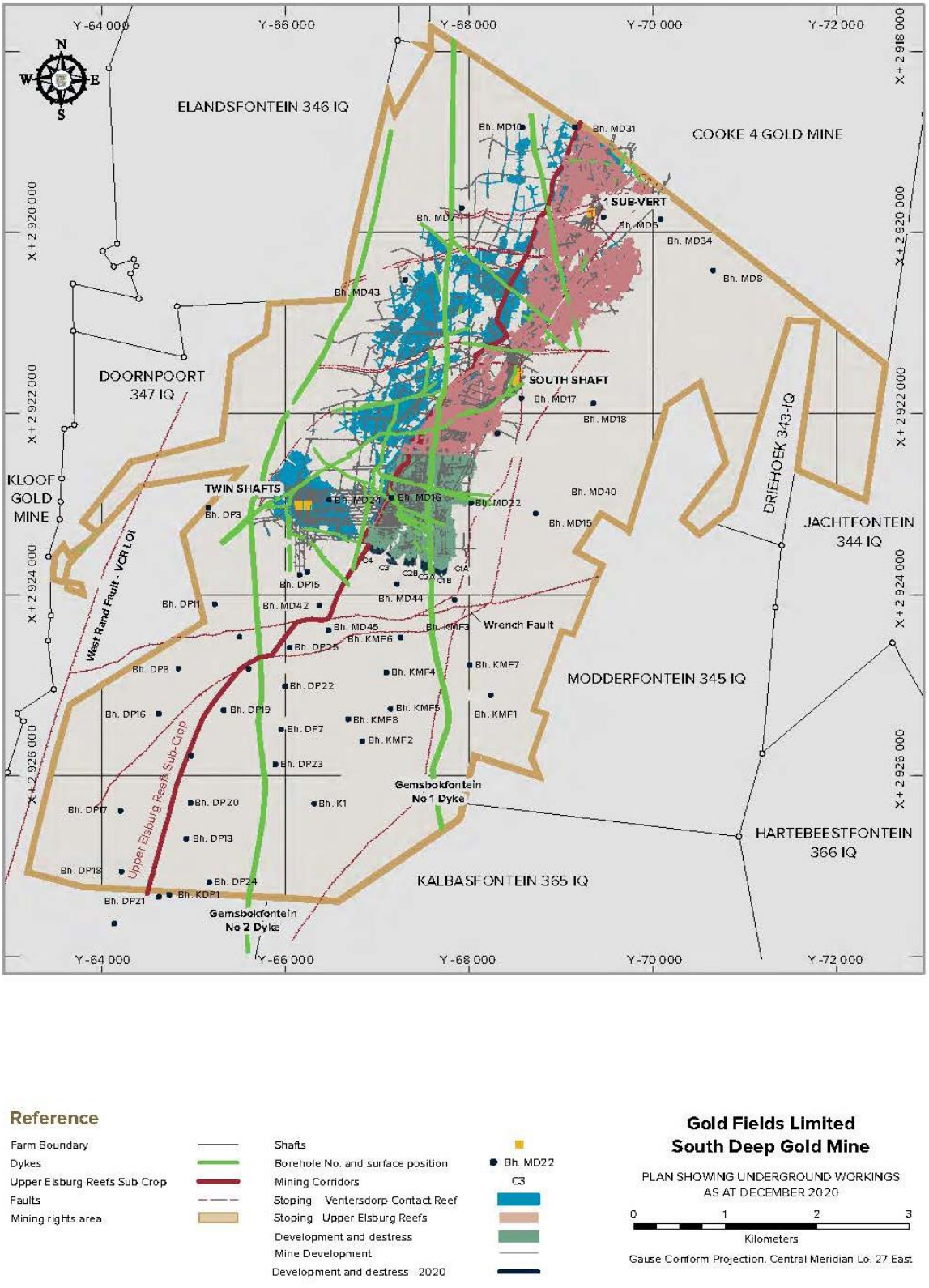


Figure 1-3: Plan of the South Deep Gold Mine mining area (Gold Fields, 2020)

The mine lies within the Witwatersrand Basin, the single largest gold-producing district in the world. This basin, whose gold origins have been argued through the placer and hydrothermal theories (Kirk *et al.*, 2003), consists of sedimentary rocks that contain conglomerate reefs with rounded pebbles wherein gold occurs. Figure 1-4 shows the geological setting of the South Deep Gold Mine within the Witwatersrand Basin.

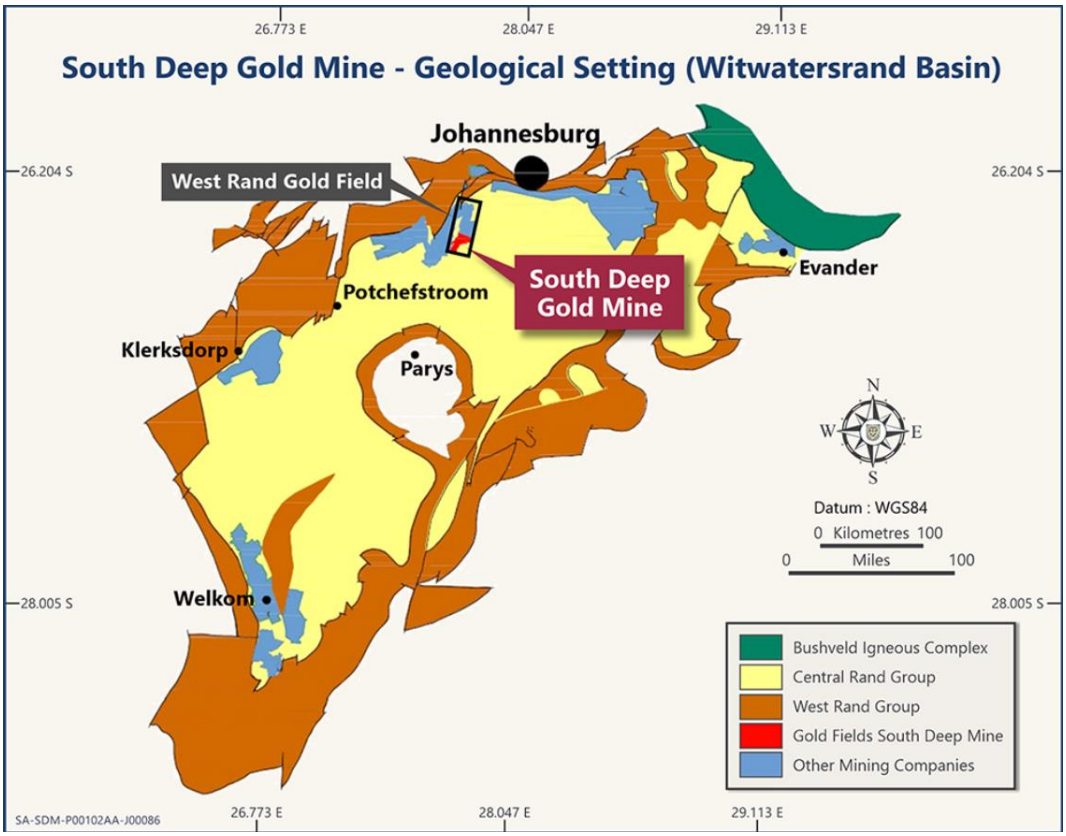


Figure 1-4: South Deep Gold Mine within the Witwatersrand Basin (Gold Fields, 2022a)

Figure 1-5 provides an isometric view of the reefs (detrital sedimentary rocks interspersed sporadically containing auriferous and uraniferous quartz pebble conglomerates (Gold Fields, 2011)) at the mine including the positions of the Twin and South shafts. Within this stratigraphic bundle are economically significant

Upper Elsburg and VCR conglomerate units. The circled area shows how the Upper Elsburg (red) forms a clastic wedge that is approximately 120m thick in the East and tappers to a thickness of about 2m against the VCR (blue) in the West (Gold Fields, 2022c).

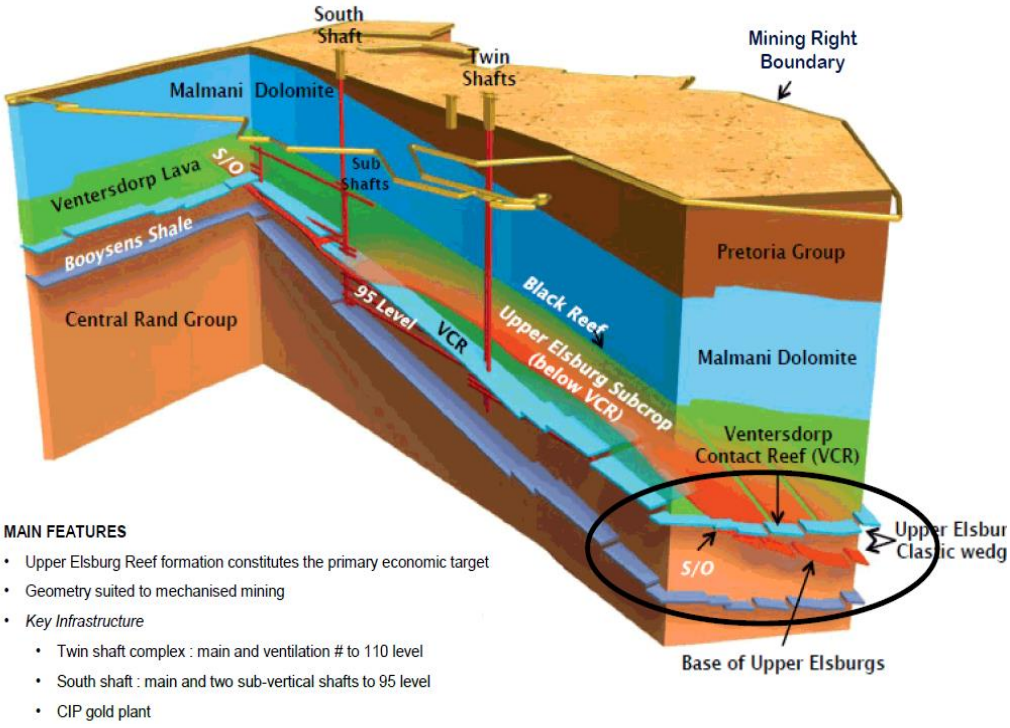


Figure 1-5: Stratigraphic view of the orebody at South Deep Gold Mine (Gold Fields, 2022c)

The Upper Elsburg conglomerates comprise Upper Elsburg Individuals of the Waterpan Member and the Upper Elsburg Massives of the Modderfontein Member (Obermeyer, 2020). Each of the members contains reef horizons that are named based on their stratigraphic positioning within their respective members and composition (conglomeratic reef or middling quartize). Nomenclature at the mine makes use of acronyms compared to full names for representing these reef horizons as shown in Table 1-1.

Table 1-1: Reef horizon nomenclature (Obermeyer, 2005)

Reef Acronym	Full Name or Description
ECB	Elsburg Individual ‘C’ Bottom Band Conglomerate
ECBA	Elsburg Individual ‘C’ Basal Band Conglomerate
ECBAQ	Elsburg Individual ‘C’ Basal Band Quartzite
ECBQ	Elsburg Individual ‘C’ Bottom Band Quartzite
ECMC	Elsburg Individual ‘C’ Middle Band Conglomerate
ECMQ	Elsburg Individual ‘C’ Middle Band Quartzite
ECT	Elsburg Individual ‘C’ Top Band Conglomerate
ED	Elsburg Individual ‘D’ Band Quartzite
MAC	Modderfontein ‘A’ Band Conglomerate
MAD	Modderfontein ‘A’ Band Degenerate Quartzite
MBB	Modderfontein ‘B’ Band Bottom Conglomerate
MBT	Modderfontein ‘B’ Band Top Conglomerate
MIB	Modderfontein Intermediate Bottom Band Conglomerate
MIQ	Modderfontein Intermediate Quartzite Band
MIT	Modderfontein Intermediate Top Band Conglomerate
VCR	Ventersdorp Contact Reef

Reef horizons beginning with ‘E’ (ECBA, ECBAQ, ECB, ECBQ, ECMC, ECMQ, ECT, and ED) belong to the stratigraphic Elsburg Individuals (Waterpan Member) where each progressively coarser stratigraphic reef horizon is represented by the letters ‘C’ or ‘D’, creating an ‘EC’ or ‘ED’ unit. Each ‘EC’ unit is further divided into either ‘BA’ for basal, ‘B’ for bottom, ‘M’ for middle, or ‘T’ for top. The ‘Q’ and ‘C’ suffixes represent the dominant lithology where distinction is needed for quartzite and conglomerate respectively (Obermeyer, 2005).

The ‘ED’ (quartz wacke) unit separates the ‘EC’ unit from the Elsburg Massives (Modderfontein Member). Elsburg Massives overlaying the ‘ED’ unit primarily consist of the ‘MA’, ‘MI’ and ‘MB’ units where the ‘M’ in each unit represents upward stratigraphic progression from the lower ‘A’ band, through the intermediate ‘I’ band, to the upper ‘B’ band. For the ‘MA’ unit, the suffixes ‘C’ and ‘D’ represent the primary lithologies conglomerate and degenerate (quartz wacke) respectively. The ‘T’ and ‘B’ at the end of the ‘MI’ and ‘MB’ units indicate whether it is the top or bottom reef horizon within a unit respectively (Obermeyer, 2005).

Figure 1-6 simplifies the clastic wedge and shows the cross-section of the Upper Elsburg orebody at South Deep. In this frame, the Upper Elsburg reefs sub-outcrop against the base of the VCR. The main target thickness for mining varies from 5m to 70m across the orebody at different corridors.

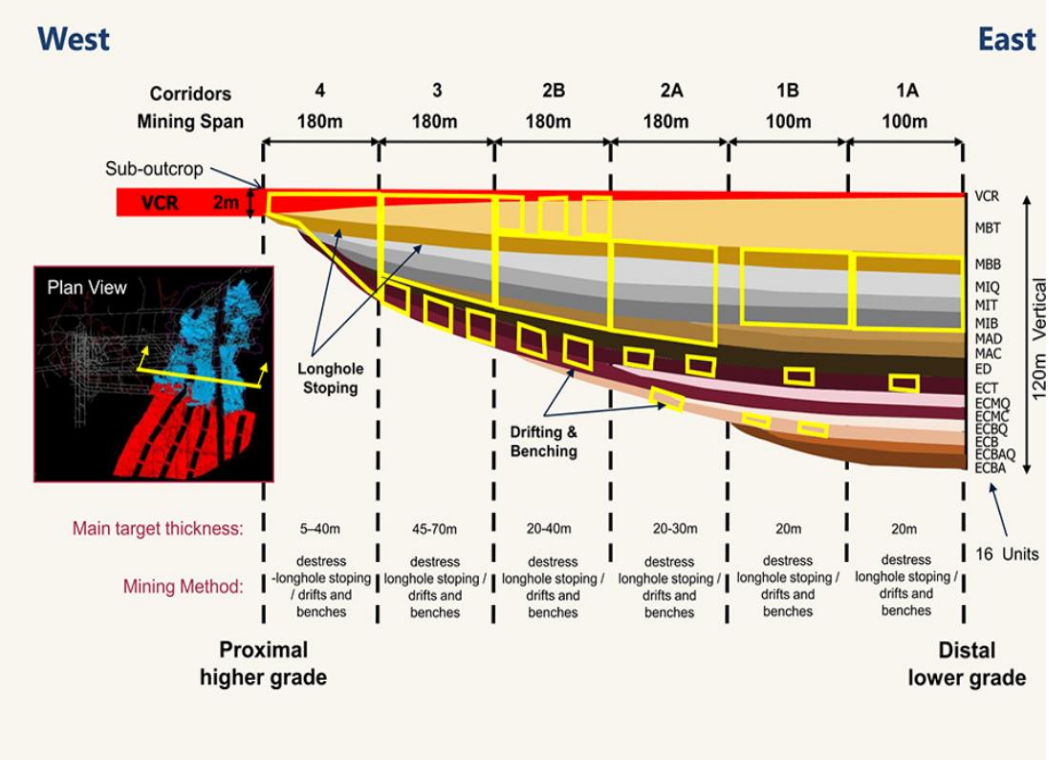


Figure 1-6: Cross-section of the Upper Elsburg orebody (Gold Fields, 2022c)

1.1.3 Mining methods

Since the mine transitioned to full mechanization, three principal methods of mining have been deployed to supply ore to the plant. The combination of the three methods, horizontal de-stress mining, long-hole stopping (LHS), and drift and bench mining is illustrated in Figure 1-7. These methods were carefully selected to balance out safety and cost-effectiveness concerns. Their combination at different levels works to ensure the mine continues to operate profitably.

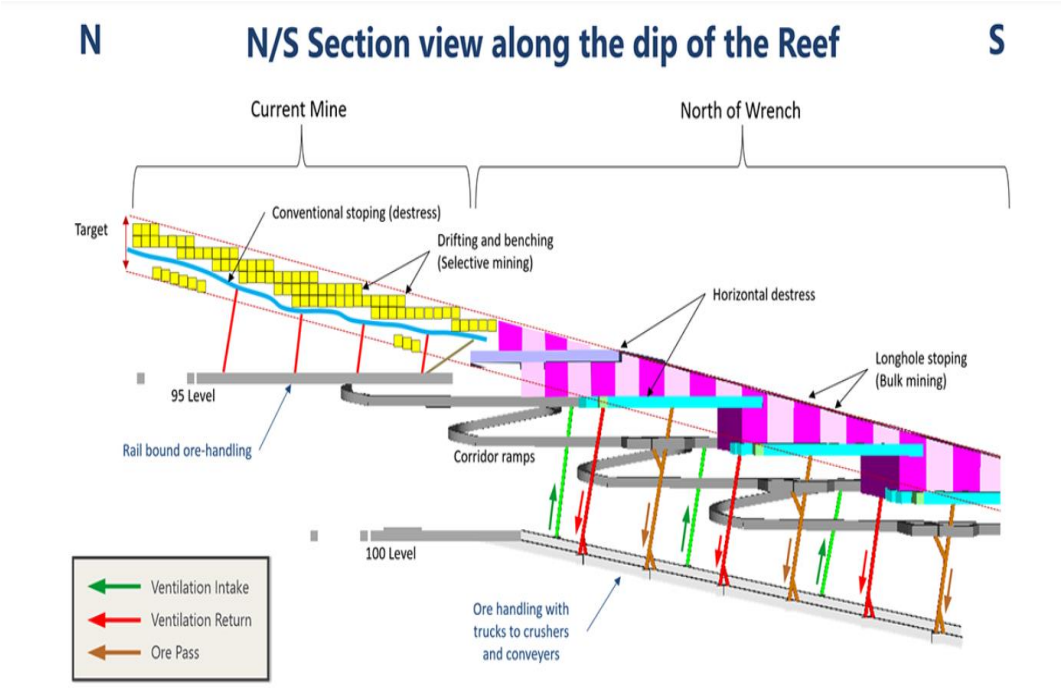


Figure 1-7: Illustration of mining methods at South Deep Gold Mine (Gold Fields, 2022c)

- **Horizontal de-stress mining**

The combination of mining at depths beyond 2500m and large excavations from mechanised mining increase rock stress levels, which when exceeding the inherent rock strength, present the risk of rock bursts that compromise safety. To deal with this problem, the mine conducts high-profile de-stressing that reduces the major stress component from about 70MPa to about 30MPa in the shadow area of the stope (Watson *et al.*, 2014).

Layered horizontal de-stress cuts overlap and reduce the stress on the large orebody target horizons. Typical de-stress cut drives are initially 5m wide and 2.2m high, with the prospect of increasing up to 5m high when integrated with Long-hole stoping. First, main access drives (MADs) are excavated along the direction of the dip, and then stope drives (SDs) are staggered parallel to the MADs maintaining a

reasonable lead/lag distance consistent with industry recommendations, (Jager and Ryder, 1999). At 15m intervals, there are stope access drives (SADs) created by cutting 5m holings though crush pillars. To reduce the chances of pillar disintegration and provide confinement, the edges of the crush pillars are filled with PowerRite^{TM} backfill bags as shown in Figure 1-8.

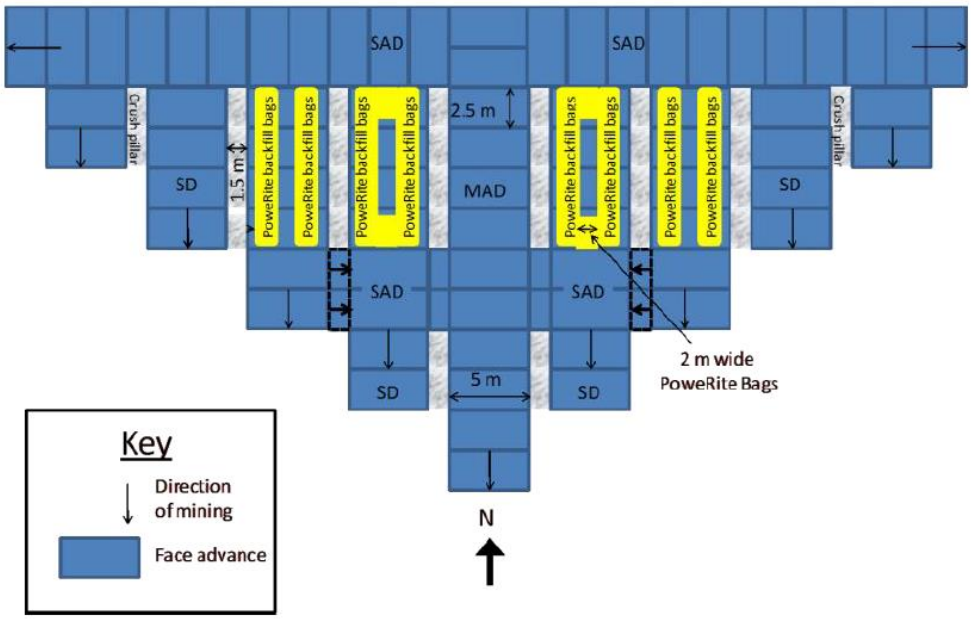


Figure 1-8: Plan view of horizontal de-stress with crush pillar layout (Watson *et al.*, 2014)

Figure 1-9 shows a de-stress concept used at South Deep. The stress conditions experienced after de-stressing in the region shown as a “window of massive mining opportunity” are similar to those that would be experienced at non-de-stressed depths of 1200m (Watson *et al.*, 2014).

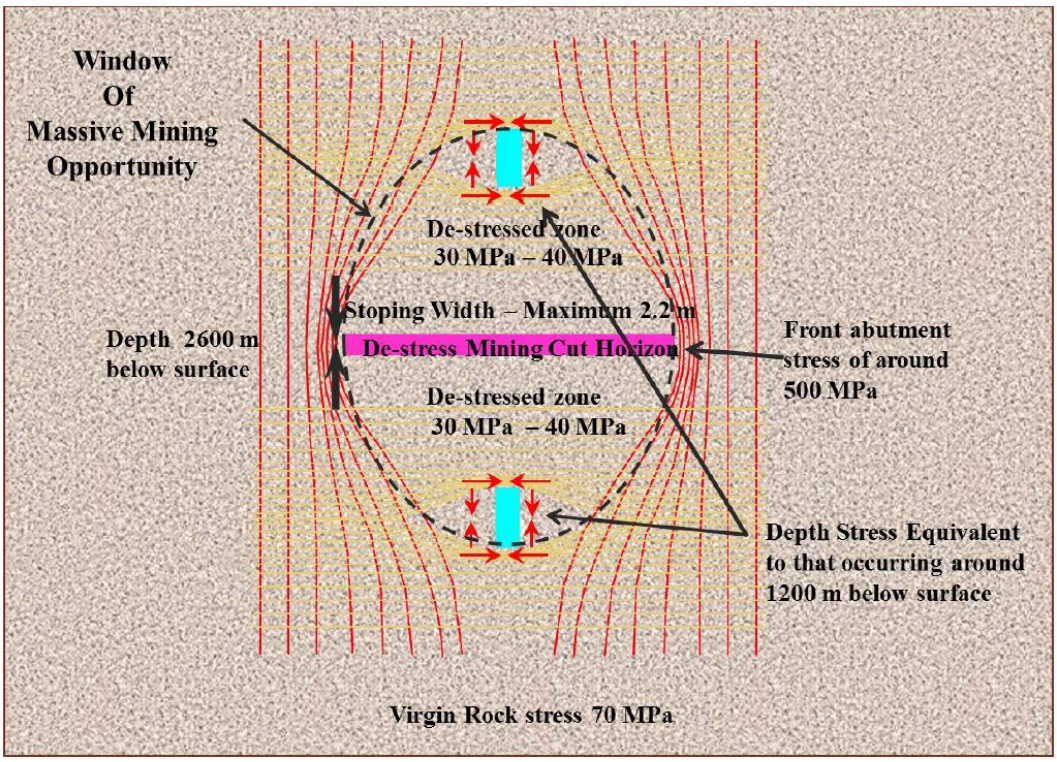


Figure 1-9: South Deep Gold Mine de-stress concept (Watson *et al.*, 2014)

An assessment of the geotechnical evolution of de-stress mechanisms at South Deep carried out by Andrews et al. (2020) showed that high-profile horizontal de-stressing creates a safer working environment with industry best-practice support standards rather than low-profile de-stressing while allowing for higher production rates.

- **Long-hole stopping**

This primary method of mining accounts for over 60% of the gold mined at South Deep. High-profile de-stressing precedes LHS and every cut follows a de-stressing then stoping progression as shown in the four stages of Figure 1-10. When stope accesses and relevant infrastructure have been set up (Stage 1), an initial cut is made and de-stressing commences (Stage 2). When de-stressing is complete for that cut, stoping begins and the next cut is de-stress mined simultaneously (Stage 3). Once de-stressing is complete in the second cut, stoping begins. At that instant,

the stope in the first cut would have matured and de-stressing would start in the third cut. This sequence continues until all the necessary cuts have been mined on a particular mining corridor.

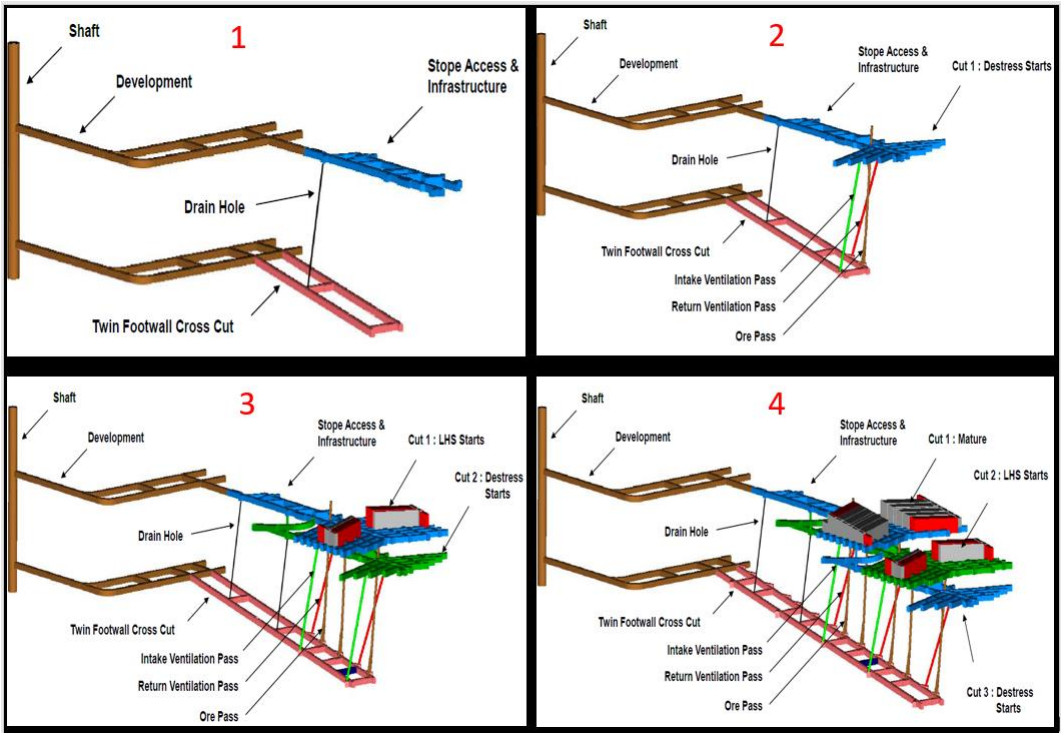


Figure 1-10: High-profile de-stress and long-hole stoping (Collated from Gold Fields (2017)*)*

Figure 1-11 shows the steps (1-5) involved in developing LHS. During development, access ramps are excavated at lower and upper levels with a separation of about 30m (Step 1). From each of these ramps, access drives with dimensions 5.5m wide and 5.5m high are developed normal to the direction of the ramps. The lower and upper drives are connected using a slot raise (Step 2) that is later extended into a full slot (Step 3) through underhand and overhand drilling. Osburn et al. (2014) add that this slot then serves as a free face (Step 4) for drilling radial fan holes that will be blasted to create stopes measuring up to 60m long,

15m wide, and 30m high (Step 5) depending on geological complexities and grade control demands.

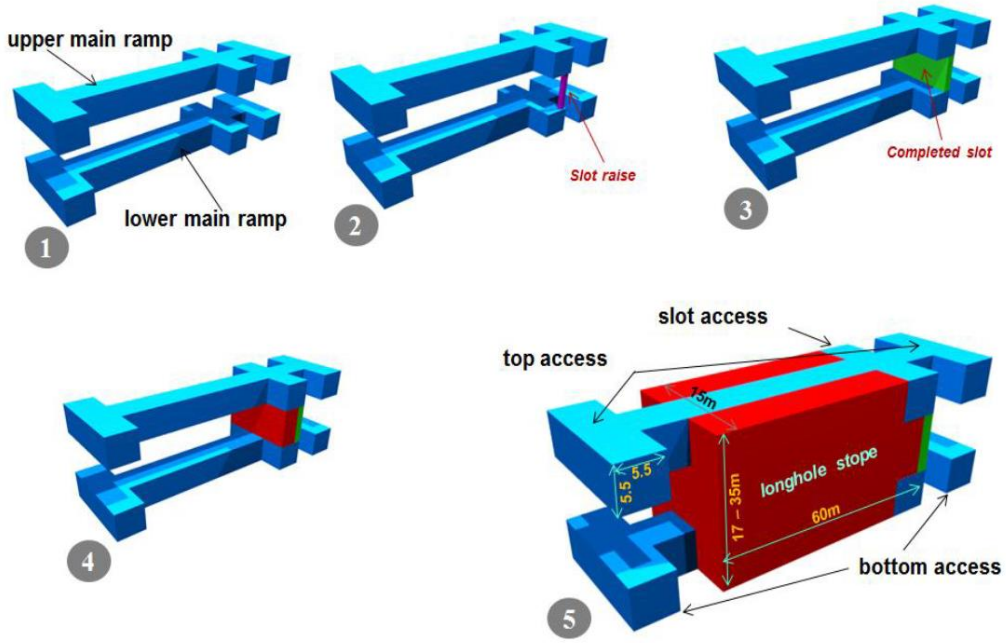


Figure 1-11: Long-hole stope development (Osburn *et al.*, 2014)

Once the fan-drilled holes have been charged and fired, they create ore that must be moved to allow for the mining of other stopes. Hauling is done using remote-controlled load-haul dumpers with bucket capacities between 10 and 15 tonnes. Post processing, some of the tailings are pumped back underground and serve as a backfill that closes the open voids. Backfilling reduces the amount of waste on surface and importantly provides stability to underground excavations. This support allows for the mining of adjacent stopes without leaving pillars of unmined ore.

- **Drift and bench mining**

This method finds vast application in areas where selective mining is required and Figure 1-12 shows the stages involved in implementing this method. The initial work involves excavating drifts perpendicularly from drift access drives using small blasts that achieve advances of approximately 3.7m per blast in a principal direction (Stage 1). The next phase involves mining benches in the opposite direction (Stage 2) through vertical blast holes at a lower elevation (Stage 3).

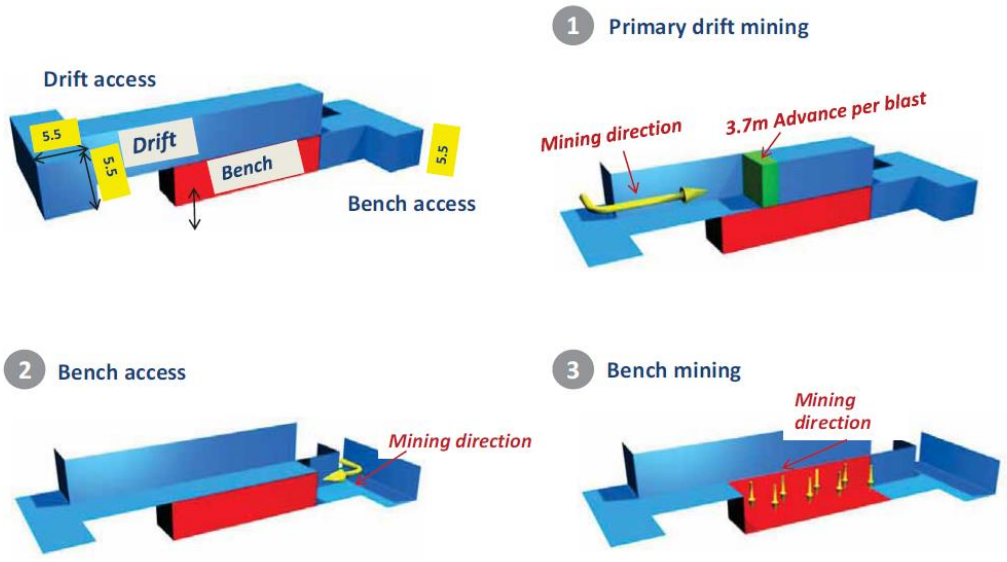


Figure 1-12: Stages and direction of mining in drift and bench mining (Gold Fields, 2013)

Broken ore from benches is mucked out using load-haul dumpers and then hauled to tipping points by underground trucks. Once a bench is completed, it is backfilled and adjacent drifts and benches are mined too with the same sequence of drifting, benching and backfilling. Figure 1-13 shows adjacent ends where drifting and benching are taking place. Primary support is attained from split sets and secondary drifts are mined in sequence retreating to the initial point of access.

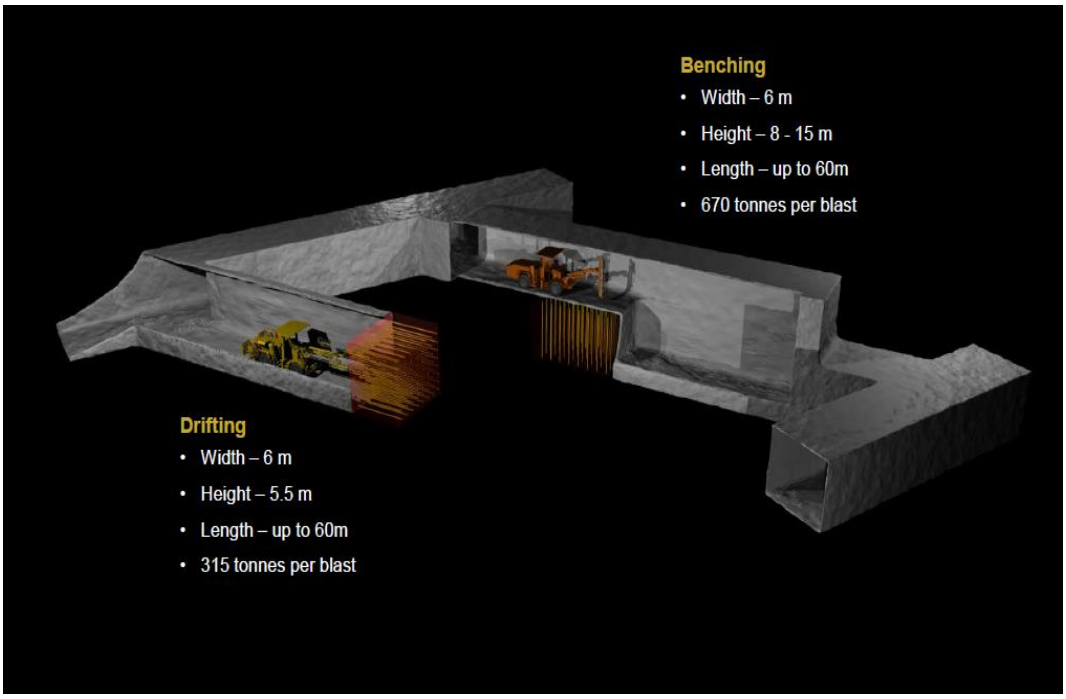


Figure 1-13: Adjacent drifting and benching faces (Gold Fields, 2017)

1.2 Research Background

After de-stressing, long-hole stopes extract large volumes of the thick Elsburg reef package. Fan holes drilled radially from stope access drives create an excavation area that takes the shape of a block. They are charged and blasted sequentially to create the retreating face. Remote-controlled load-haul dumpers remove broken ore from stopes and the mined-out cavities are backfilled with waste material. According to Hamrin (1982), larger stope dimensions increase mining efficiency and the limiting factor in stope and pillar size selection is the stability of the rock mass.

Longer stope turnaround times at South Deep cause underutilisation of the installed capacity. Ore is not moving out of stopes because of the difficulty associated with poor excavation stability and inconsistent blast fragmentation.

Stope failures are drill and blast-induced, structural, or due to large span diameters.

The influence of stope type and mining environment on stope stability is unknown. There is also a gap in defining a failed LHS and zones where failure is prevalent in the context of South Deep. The exact location of over-break (O/B) and under-break (U/B) is unknown and there is uncertainty over the correct way of calculating them. Lastly, the influence of drilling and blasting practices on fragmentation and subsequent loading is unclear.

1.3 Purpose of the Study

Over 60% of the gold produced at South Deep Gold Mine comes from LHS. The capacity of a mine to produce ore is severely constrained by the stope turnaround time (Potvin & Hudyma, 2000). It is therefore critical that the stopes meet the required production output for the designed mine lifespan at efficient stope turnaround times.

However, mine data suggests that ore production from LHS has been erratic and has significantly affected the mine's ability to produce to its installed capacity, that is, the maximum production output attainable at the mine subject to equipment and infrastructure constraints. Figure 1-14 shows a reproduced extract of an executive summary from a 2021 South Deep Gold Mine drilling and blasting stope health report. It shows how most LHS deviate from the planned design tonnage.

Executive Summary				
Stope	Current Planned Tons	Current Actual Tons	Legend	
			Compliance	Overbreak
			%	%
			85-100	<31
			70-84	31-40
			0-69	>40
90 1BW CUT02 LHQ 02B	2772	3157	80	34
100 1BW CUT04 LHQ 5W	3157	2763	70	18
100 01BW CUT04 LHQ 7W	2481	6305	100	52
095 1W CUT05 LHP 01N	3934	5132	100	25
100 2BW CUT04 LHP 01W	3762	2665	56	15
100 4W CUT04 LHQS 10E	3797	7708	92	111
100 03W CUT02 LHQ 01W	2757	4520	100	49
100 03W CUT03 LHP 06W	1112	1845	93	73
100 04W CUT05 OSL 01E	832	657	72	7
095 02W CUT03 LPLS 02S	4048	10787	100	166
100 04W CUT04 LHQS 04S	1772	2782	93	64
100 4W CUT02 LHPS 04N	650	2578	90	307
100 1BW CUT04 LHS 08E	2532	3281	60	70
100 2BW CUT02 LPLS 01S	1263	2540	99	102
100 2BW CUT02 LPLS 02S	560	607	77	31
100 04W CUT02 LHS 04E	4236	5806	87	50

Figure 1-14: South Deep Gold Mine LHS performance (Reproduced from Gold Fields(2021)*)*

The reduction in productivity and utilization is an area requiring research and this project investigates LHS performance at the mine to understand factors that influence stope turnaround time. This goal will be achieved through generating stoping scenario charts and statistical models for decision-making, informing excavation design as well as reviewing drilling and blasting practices.

The research considers the analysis of LHS files containing stope profiles, characterisation of mining environments, development of stoping scenario graphs and statistical models as well as leveraging on intersections that exist between the mining environment, technical design elements, and operational tactics at the mine.

1.4 Problem Statement

At South Deep Gold Mine, LHS are mined across unique mining environments such as below de-stress cuts (DC), below conventional stopes (CV), below lava (LV), below open developments (OD), below open stopes (OS) as well as below solid ground (SL). Current practice at the mine yields over 30% over-break across the different environments, compromising stope stability. This poses a safety risk and reduces the volume of extractable ore as previously observed in Figure 1-14 where some stopes have stope compliances as low as 56% and 60%. Loading challenges arise and increase the stope turnaround times, upsetting the balance of production planning.

As a mine standard, South Deep LHS should yield less than 30% bad-break and have fewer instances of secondary blasting. The mine has no guiding charts or processes to inform the suitability of stope designs for the various environments. For some environments such as BL, there is ambiguity over the calculation of over-break, for instance, the decision whether to incorporate the portion of 3m thick rock skins that fall off with every blast.

1.5 Research Motivation and Justification

The research will show the importance of designing LHS that take cognizance of the mining environments in which they are located. This will reduce a generalization in stope design, which is costly because environments react differently to excavation. Apart from reducing stope turnaround time, the research will yield downstream benefits such as improved ore flow, better ore accountability, higher utilization of installed capacity, reduced dilution, and compliance with the mine plan (Ibarra et al., 1996).

The study contributes to the body of knowledge for deep-level mines with unique geological environments looking to improve the performance of their LHS. It shows alternative approaches specific to the context of South Deep Gold Mine to assess LHS performance. Implementation of operational change associated with insights from this research has the potential to significantly reduce the amount of dilution, which has downstream effects of increasing revenues. Lastly, the project lays a foundation for the evaluation of other systems at the mine by suggesting areas for further study.

1.6 Research Questions and Hypothesis

The overarching question of the research will be; how do different factors influence LHS performance at South Deep Gold Mine? Three specific questions will be answered.

1.6.1 What is the influence of geological environments on long-hole stope performance?

This question will bring an understanding of what is considered a failed LHS in the context of South Deep Gold Mine. It will show how different mining environments (stopes mined under lava, conventional stopes, de-stress cuts, open developments, open stopes and solids) and reef horizons influence stability. Finally, it will establish the stope surfaces (crowns, footwalls (FW), hanging walls (HW) or sidewalls) on which failure and poor performance are prevalent.

1.6.2 How do design aspects at South Deep Gold Mine affect long-hole stope performance?

This question seeks to understand the effectiveness of stand-offs, for instance, below lava, when designing LHS as well as the optimum distances. It will further interrogate how different mining sequences (primary, secondary, sequential) influence stability and indicate the pervasive stope failure types.

1.6.3 How do current drilling and blasting practices affect long-hole stope performance?

The last question looks at how drilling and blasting practices (tamping, burdens, charging, timing, hole deflection, direction, water) influence fragmentation and how in turn fragmentation affects loading times. It will also facilitate understanding where under-break and over-break are situated as well as establishing if they are being calculated in a practical way using current conventional methods.

The null hypothesis will be that a universal invariant approach to mining the different environments is capable of improving LHS performance. The alternative hypothesis tested will seek to show that mining environment-specific design and operational approaches can significantly improve LHS performance.

1.7 Research Aim and Objectives

The study aims to improve LHS performance by reducing stope turnaround time. Answering the research questions will help understand how the factors that influence LHS performance create a leeway to improve stope turnaround time. This will help achieve these objectives:

- Establishing empirical design charts and statistical models for different stoping scenarios or a combination thereof;
- Informing excavation design; and
- Reviewing drilling and blasting practices to limit under- and over-break to the mine's desired maximum of 30%, reduce the occurrence of secondary blasting and yield fragmentation ideal for loading.

The objectives listed will operate in tandem to provide the desired effect.

1.8 Sources of Data and Assumptions

The following assumptions will guide the research:

- LHS data files are accurate and precise as they are compiled by the survey department and then shared with the rock engineering and drill and blast departments on Deswik software. Deswik is a suite of applications that enables operators to make better and faster decisions with digital access to production data. The software offers seamless and accurate information exchange between several elements of a mine plan, for instance geology, design and scheduling (Bulbulia, 2018);
- Data from mine documents represents the best picture of what is happening at the mine; and
- Various mining environments respond differently to the same drilling and blasting practices.

1.9 Research Methods

The research will seek to leverage knowledge gathered on the intersection between the mining environment, technical design elements and operating tactics

at the mine. To this end, the approach will be that of first categorising the unique mining environments into districts/zones.

An analysis of LHS files containing empirical data for different stopes will be carried out. This will lead to the development of charts showing among other things the variability of over-break with hydraulic radius (HR) for each of the mining environments. It will also provide an insight into the influence of stope type and mining environment on stability. The charts will also be used as criteria for defining stope failure.

The data will also be used to develop a statistical model for the prediction of over-break and under-break on stope surfaces as well as a design matrix for managing poor LHS performance. The matrix and model will guide excavation design/techniques, support systems, and extraction ratios in the various environments.

Next, the project will look extensively at the operational elements of practice like drilling and fragmentation. It will compare the standards of operations laid down on paper with what happens underground. Understanding the intersection of the mining environment, technical design elements, and operational tactics will help formulate recommendations for best practices to reduce stope turnaround times. Figure 1-15 summarises the approach to conducting the research.

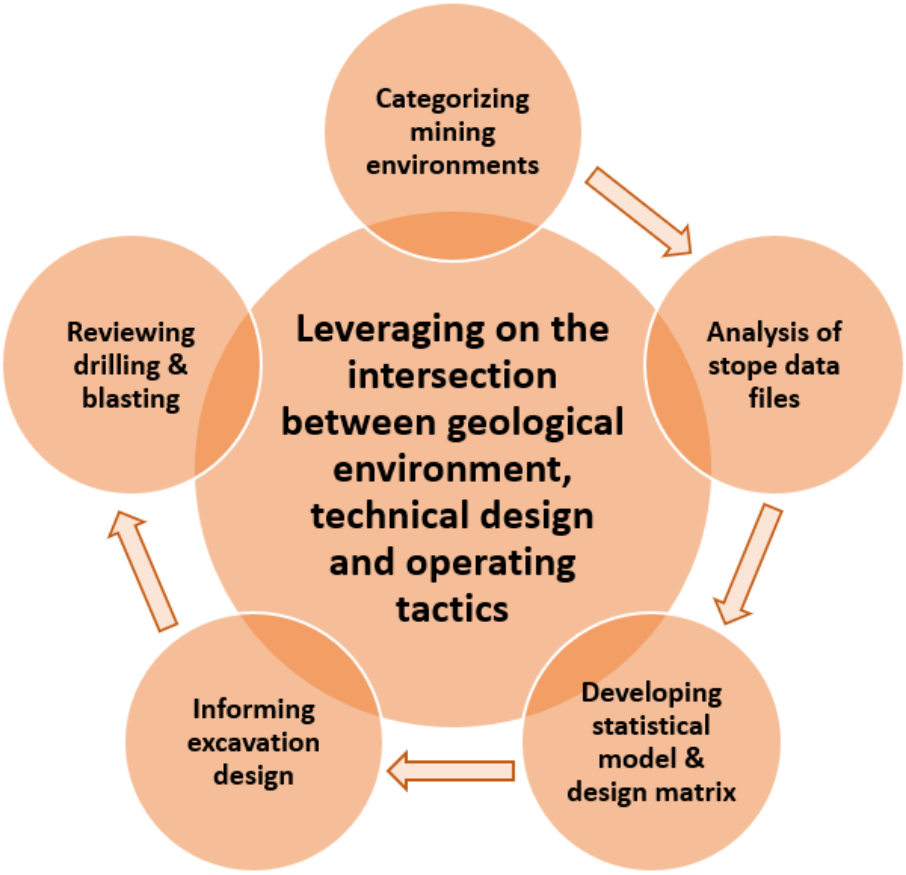


Figure 1-15: Research methodology

1.10 Structure of Report

The first chapter of the research, the Introduction, provides a background of the mine, highlighting its history, location, and the methods of mining used. The Introduction will also give a background of the research, showing the purpose of the study, the research motivation, questions, aim, and objectives. It will finish off with a summary of the approach used to conduct the research. The Literature Review will be the second chapter covering scholarly work on the past and present state of the problem under review. It will also provide a critical review of previous investigations of closely related problems.

The third chapter, Methodology, will lay down the route of research execution as well as data collection means. Results and Analysis will be the fourth chapter where findings of the investigation will be presented in the context of the research questions. This will explore the results regarding their meaning and implication to the research questions. The fifth chapter, Conclusion and Recommendations will summarise the extent to which the objectives were achieved and propose strategies for addressing the problem.

2 LITERATURE REVIEW

This chapter provides a review and identifies gaps in past and present scholarly work on the subject of LHS, all of which will be critical in investigating the performance of the stopes at South Deep Gold Mine. It also looks at closely related work done by other scholars to provide theoretical guidance as well as a backing for the assumptions made in conducting this research.

2.1 Long-hole Stoping

Hartman (1992) defines LHS as an open stoping, high production, bulk mining method applicable to large, regular ore-bodies having competent ore and rock that require little or no support. Nomenclature differs with scale, with other authors (Hamrin, 1982; Henning, 2007; de la Vergne, 2008) using the term interchangeably with variants of blast hole stoping or sublevel open stoping. Hartman and Mutmansky (2002) developed a mining method chart that guides the method of mining to be selected based on orebody geometry and ground conditions as shown in Figure 2-1.

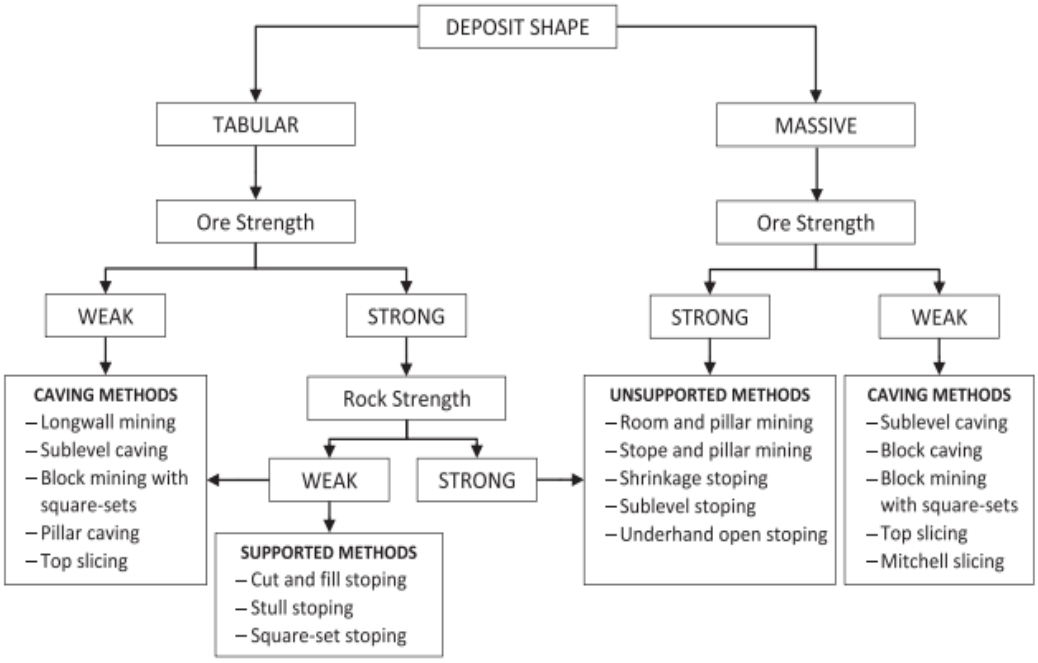


Figure 2-1: Hartman and Mutmansky selection chart (Hartman & Mutmansky, 2002)

This method offers limited selectivity and is best suited for ore-bodies that are vertical or steep-dipping as highlighted by Balt and Goosen (2020). Ground conditions determine stope dimensions (Henning, 2007) and the largest dimension is usually the vertical one as shown in Figure 2-2.

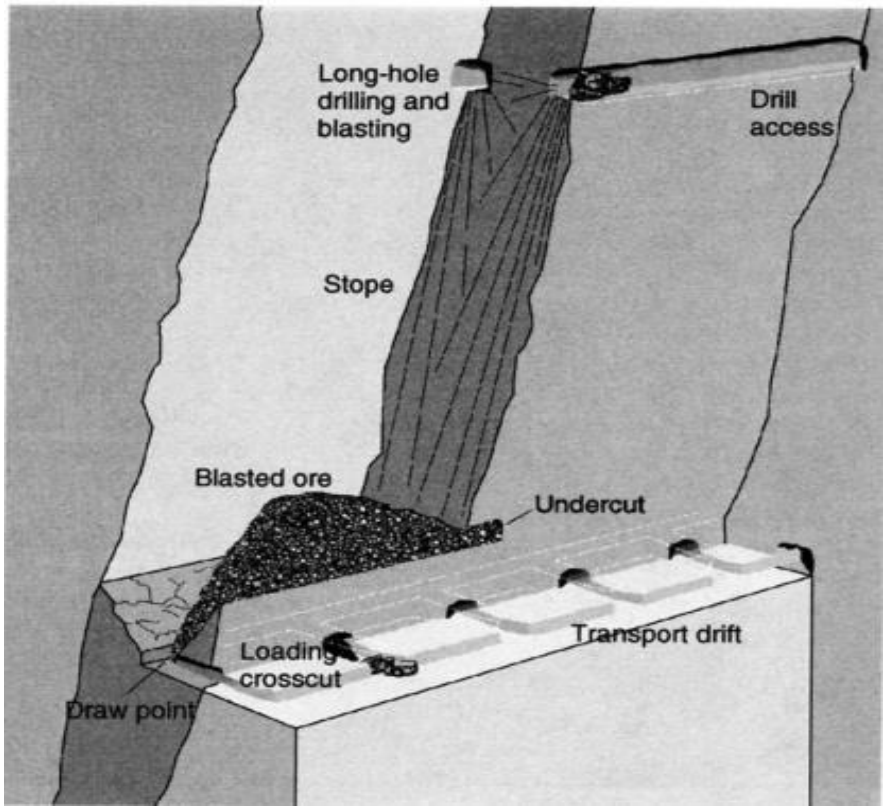


Figure 2-2: Long-hole stoping (Hamrin, 1982)

In this system of mining, large-scale drilling and blasting occur to break huge amounts of ore in single blasts. The broken ore falls into large empty voids created and are cleared using load-haul-dump units. The next phase of the operation involves using consolidated backfill to aid stability and allow for the extraction of pillars.

With such mining occurring at deep-levels, it is important to consider immediate threats that are associated with the method. Stress increases with depth and according to Xie et al. (2018), it is significant to master mining-induced stress distribution in deep-level mining. Once stopes have been excavated, they need to be filled so that they provide adequate support. Finally, stopes have to be completed on time to prevent compromising the production rates.

2.1.1 Stress and de-stress mining

Brady and Brown (2004) show how virgin stress in rocks increases with depth as illustrated in Figure 2-3. This is an ever-present challenge that exposes the mine to the dangers of rock bursts (Wagner, 2009). To access deep-lying minerals, mines have to apply mechanisms that reduce the concentration of stress in underground workings. Ozbay et al. (1995) express that for shallow mines, pillar strength should suffice to withhold the stress exerted by excavation. However, mining at depth raises the need to better manage stress, thus some mines employ de-stress mining.

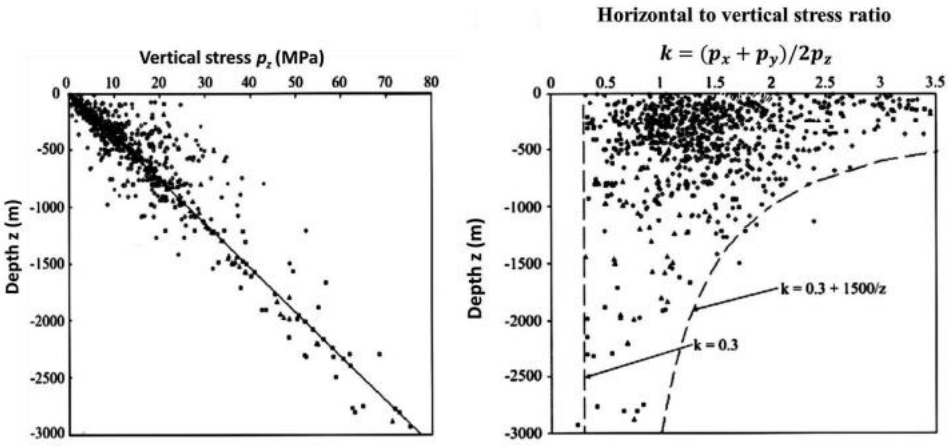


Figure 2-3: Variation of rock stress with depth (Brady & Brown, 2004)

Konicek and Schreiber (2018) mention that the main goals of de-stressing are to soften competent rock layers, reduce strain energy storage, and release rock mass stress, which together contribute to minimise rock burst occurrence and risk. De-stress mining methods utilise the de-stressing philosophy, where a tabular mining cut is made in the target package to de-stress the rock below and above it (Andrews et al., 2020).

Watson et al. (2014) have shown that de-stressing at depth can create environments whose stress conditions are similar to shallow non-de-stressed environments. De-stress cuts can exist as low or high-profile as observed through the experiences of South Deep Gold Mine by Andrews et al. (2020). An ideal de-stressing cut yields a balance of benefits in ground support systems, ground performance, production, seismicity, and backfill requirements. High-profile de-stressing methods hold an advantage over low-profile ones in that they allow for the installation of mechanised ground support, release less seismic energy, and create a safer working environment congruent with industry standards (Andrews et al, 2020).

2.1.2 Backfilling

One critical component of deep-level underground mining operations is the backfilling of mined-out areas. Masniyom (2009) defines backfill as the material(s) that are used to fill void openings of underground mines for mining technical or mining safety purposes. The use of backfill allows for a range of engineering solutions in mines including improvement of rock stability, better ore recovery, reduction of subsidence effects at surface, reduction in the cost of constructing significant tailings disposal structures, reduction of environmental footprint, improvement of mine ventilation as well as prevention of fires and explosions (Rankine et al., 2007; Sheshpari, 2015; Qi & Fourie, 2019). Figure 2-4 shows the history of mine backfill with cemented paste fill (CPF) gaining more traction in modern-day operations due to its technical, environmental, and economic benefits.

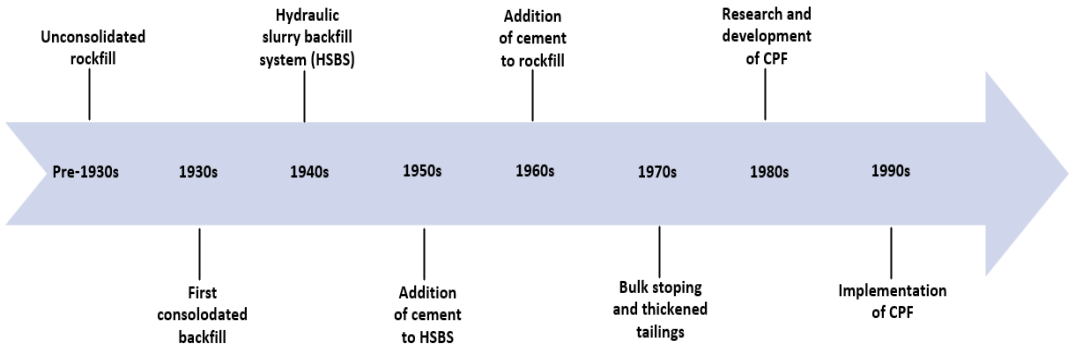


Figure 2-4: History of mine backfill (Qi & Fourie, 2019)

Yowa (2018) summarises the common types of backfill used in underground mines. Uncemented rock fill (URF) is the cheapest and easiest backfilling method where unconsolidated waste rocks from blasting are directly dumped into stopes. With cemented rock fill (CRF), cement is used as a binder in a dosage of 4-7% of the dry rock fill mass before the mixture is disposed into stopes. Cemented aggregate fill (CAF) is similar to CRF, but instead of rocks, the method utilises crushed aggregates mixed with a binder in a CAF plant.

Hydraulic fill (HF) makes use of coarse mill tailings that have been de-slimed and had their clay particles removed. The tailings are transported as slurry to the underground stopes. Cemented hydraulic fill (CHF) applies the same concept as HF and further adds a binder to reduce water and consolidate the tailings. The most common method of backfilling is cemented paste fill (CPF) which is produced at a surface paste plant by mixing and agitating the mill waste tailings with water, binder, and additives. The consistent strength development paste (Qi & Fourie, 2019) is transported through reticulation lines and disposed of in underground stopes.

2.1.3 Stope turnaround time

According to Malan (2003), the rates of drilling and removing blasted ore from draw points largely influence stope turnaround time (from the start to the completion of a stope). Clearing muck on time allows for the drilling of the next round, facilitating the quick completion of a stope (Copland & Nehring, 2016).

Longer stope turnaround times mean that mining of adjacent ore reserves is delayed until the primary stope is mined, filled and the fill has set. Potvin and Hudyama (2000) add that additional material from over-break lowers stope productivity and increases the turnaround time. Increased mucking time means that other stopes must be brought online early to meet production targets (Cepuritis & Villaescusa, 2006).

2.2 Mining Environment

2.2.1 Stope location

Heidarzadeh et al. (2021), show that stoping may occur in heterogeneous environments underground. LHS may be excavated in mines with one or a combination of environments including below lava, below tabular voids, in blind stopes, below as well as next to backfill. Stope design in these environments therefore requires attention to the dynamics of the surroundings.

Generally, the Witwatersrand Basin contains thin, unconformity-bound, conglomerate reef horizons (Safanov & Prokof'ev, 2006; Tucker et al., 2016). However, the Upper Elsburg reef horizons are unique in that they have massive and thick conglomeratic beds as well as basal unconformities alternating with overlying quartzites (Obermeyer, 2020). The uniqueness of these reef horizons at

South Deep Gold Mine opens stope design to a specialised approach different from most mines within the Witwatersrand Basin.

2.2.2 Stope mining sequence and stope categories

Despite being suitable for mining by Long-hole stoping, the safe extraction of an orebody requires that it be mined in volumes smaller than the orebody itself (Villaescusa, 2003). The stope mining sequence guides how the extraction of stopes occurs. The main driver for sequencing is ore grade (high grade first) although it is also used to manage stress distribution and concentration as well as overcoming operational challenges such as backfilling, ventilation, access, and draw point frequency (Ghasemi, 2012; Tommila, 2014). Sequencing thus becomes pivotal in ensuring mining flexibility and maintaining a sustainable extraction rate.

Within a mining sequence, the environment surrounding a stope determines what category it falls into. There are two common stoping categories, primary and secondary. Stopes bound by rocks above and on both sidewalls are primary stopes, while stopes that may have backfill on one or both sidewalls are classified as secondary stopes.

The timely completion of primary stopes and their backfilling allows for the mining of secondary stopes, presenting more stopes to work with and increasing productivity. Table 2-1 shows possible stope categories based on the setting within the mining sequence while Figure 2-5 illustrates the primary and secondary stope mining sequence categories. The shaded areas represent areas that have been mined and backfilled.

Table 2-1: Potential stope categories based on setting within mine sequence

Stope Category	Code	Description
Primary 1	P1	Rock on both sidewalls. The stope is located one lift above the fill horizon
Primary 2	P2	Rock on both sidewalls. The stope is located two lifts above the fill horizon
Primary 3	P3	Rock on both sidewalls. The stope is located three lifts above the fill horizon
Secondary 1	S1	Rock on one side. The other stope wall is against the backfill. Also considered as pillar-less stope extraction
Secondary 2	S2	Both sidewalls of the stope are against backfill.

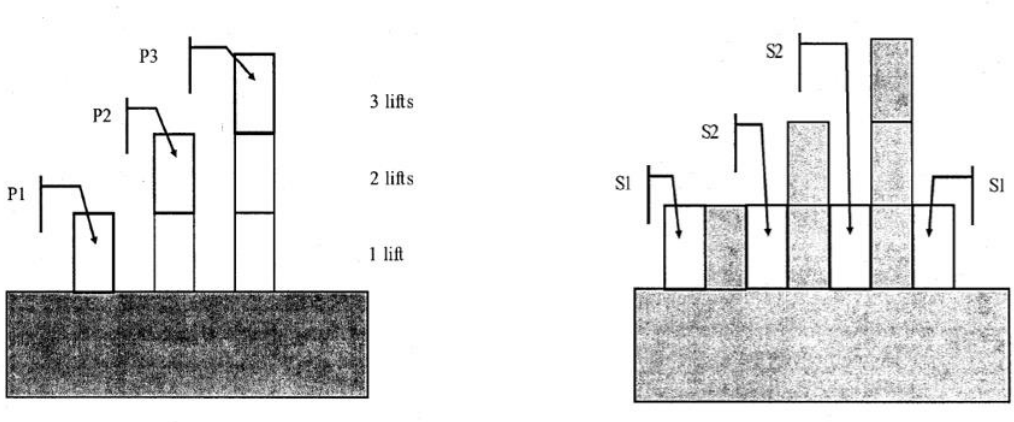


Figure 2-5: Primary and secondary stope mining sequence category (Henning, 2007)

2.2.3 Geological complexities

More O'Ferrall and du Plessis (2017) consider the influence of geological structures as an important aspect affecting the stability of operating mines. The

presence of dykes, faults, joints, fissures, contacts, and other complexities that compromise rock integrity and excavation stability affect the performance of excavated LHS. In recognising the disruptive nature of geological structures in underground operations, More O'Ferrall & du Plessis (2017) acknowledge that an understanding of the formation, characteristics and orientation of these structures is essential in the determination of appropriate stope design and overall stope stability.

Strata control problems arise in geologically disturbed regions where the intensity of mining-induced stress fractures is high and meets a high degree of faulting or a frequent geological feature. These intersections contribute to rockfalls and bad breaks, hence the need to incorporate them in the design of LHS (Quaye & Guler, 1998).

2.3 Long-hole Stope Performance

Stope performance is quantified through the reconciliation of the achieved excavation concerning the planned geometry. The amount of over-break (material unintentionally mined) and under-break (material intended to be mined, but not recovered) resulting from mining a stope significantly determine the performance and value of that stope (McFadyen *et al.*, 2020). Desired fragmentation consists of material intended to be mined and recovered whereas undesired fragmentation consists of over-break and under-break.

Henning (2007) considers four categories of factors that influence over-break (i) initial design, (ii) stope excavation, (iii) stope recovery, and (iv) data integration. These categories can be applied in illustrating relationships between factors that

influence LHS performance. Figure 2-6 shows an iterative relationship where initial design and stope excavation determine the success of stope recovery, while data integration serves as a guideline for future stope design.

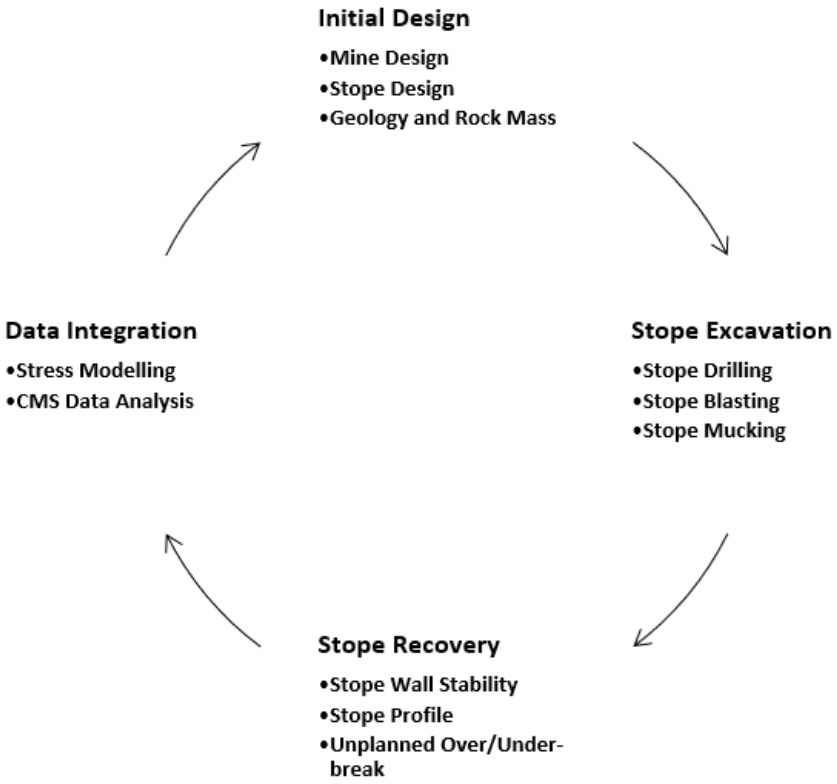


Figure 2-6: Stope performance categories (Modified from Henning (2007)*)*

According to Cepuritis and Villaescusa (2006), the success of an open stope can be judged based on the actual outcome versus the planned outcome. This considers the final volume, tonnage and grade of material expected, and the timeliness of extraction, compared to the planned design and schedule. Based on assertions from both sets of scholars, it is evident that over-break and under-break are the main physical criteria for assessing stope performance. They directly influence the stope turnaround time.

Having appreciated the uniqueness of the environments under which stoping occurs, it is critical to reconcile stopes and assess their performances based on factors influencing that particular environment. Tshabalala and Pretorius (2021) propose the application of quality and reliability management tools to improve LHS performance.

Mines may also consider stope performance assessment from a geotechnical perspective and reconcile stopes at finer resolutions. This typically quantifies stope performance on a per-face basis, for instance, concerning the hanging wall, footwall, or side wall. Such assessment allows for a deeper understanding of the influence of geotechnical factors on performance. It also enables the expression of recommendations in the context of the used faces, for instance, changing the drilling angle to minimise over-break on the side walls.

Quantification of stope data can be achieved through analysing two-dimensional plan maps or by using software like mXrap and Deswik. A combination of these methods allows for a better analysis of stope performance as they complement each other.

2.4 Stope Failure

Failure occurs when the original state of the rock mass surrounding the excavation is disturbed beyond the limits it can bear, reducing the period a stope stands (Idris, 2014). Failed stopes are difficult to access and pose a danger to humans and equipment (Wang *et al.*, 2007). Sewnun et al. (2018) argue that stope failure occurs in forms such as plastic yielding, macroscopic boundary cracks, and the spalling or complete collapse of excavation. Consequently, recognising the damage

process and subsequent failure modes plays a critical role in the assessment of stope instability.

Disturbance can come from drilling and blasting, seismicity and/or large design spans. While the impacts of large-span designs and drilling and blasting are direct and within human control, seismicity poses a greater threat due to its complex nature.

2.4.1 Seismicity

Larson (2004) defines seismicity as the rock mass response to deformation and failure while a seismic event is the sudden release of potential energy stored in the rock. For a seismic event, the released energy is radiated as seismic waves. Seismic events are either associated with stopes (occurring as strain or pillar bursts) or associated with geologic continuities (occurring as fault slips or shear raptures). Figure 2-7 is a flow chart developed by Ortlepp (1997) to show how a seismic event occurs once all source mechanism conditions have been met.

A rock burst is a mining-induced seismic event that causes damage to rock openings (Larsson, 2004). Different authors categorise rockbursts based on the following methods of classification:

- Amount of rock displaced, maximum magnitude, amplitude on seismograph (Scott, 1988; Scott et al., 1997);
- Distance from/effect inside mine workings (Bigarre et al., 1993; Vervoot & Moyson, 1997);
- Relation to mining situation and stress level (Knoll & Kuhnt, 1990; Hedley, 1992); and

- The underlying mechanism causing seismic events (Gill et al., 1993; Yi & Kaiser, 1993).

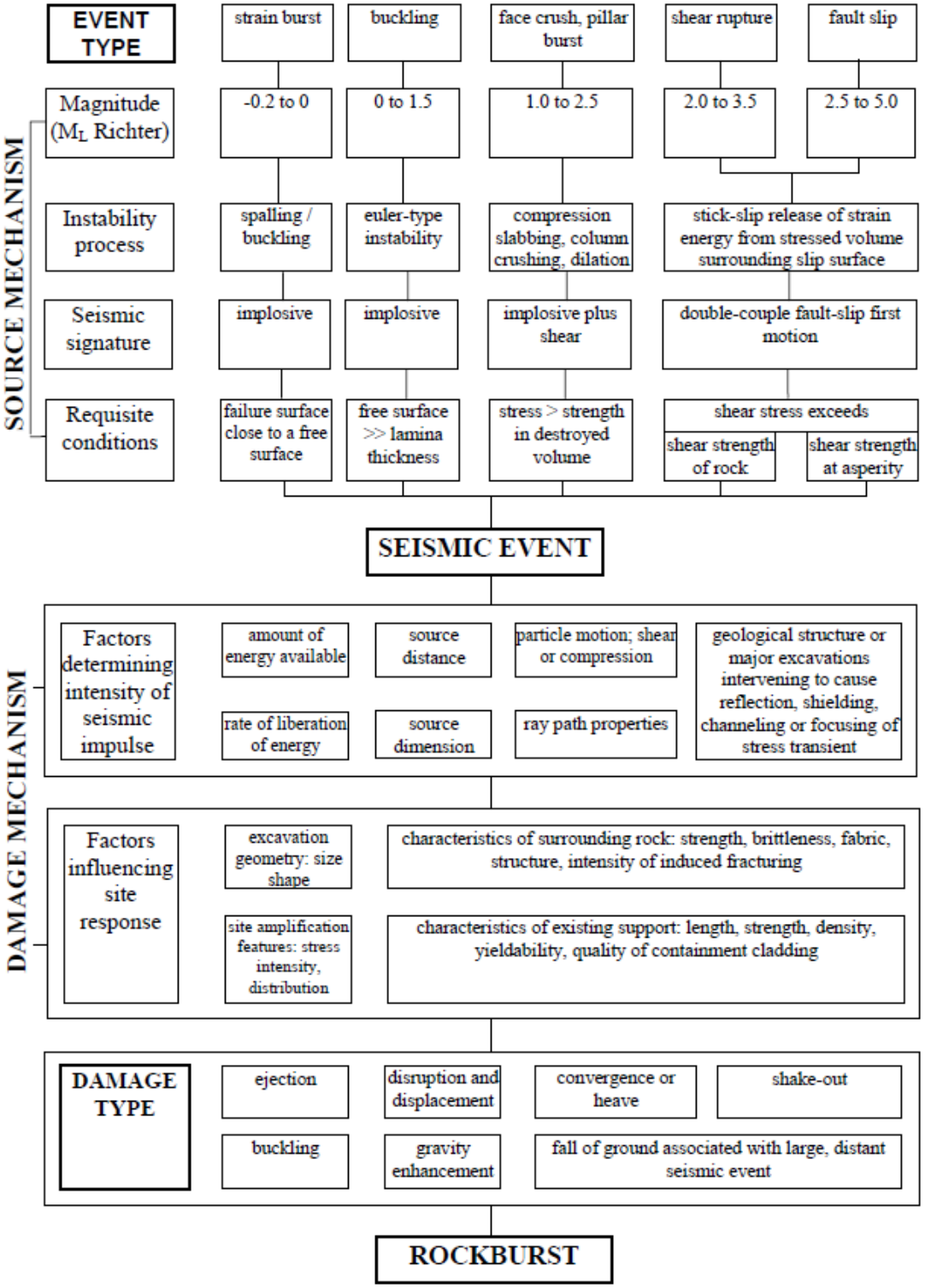


Figure 2-7: Rockburst flow chart (Ortlepp, 1997)

2.5 Excavation Stability

Stability evaluation for a proposed underground excavation is the fundamental step in designing an excavation (Stacey, 2001). For stability evaluations, it is important to consider a sequence that tests for rock failure, structural instability, stability of beams, and rock mass instability. This allows for the optimisation of the excavation concerning location, orientation, shape, and size (Pontow, 2019). In empirical stability analysis, the following concepts should be understood.

2.5.1 Q system

Barton et al. (1974) developed one of the two prominent methods of rock mass classification, the Q system. This parameter is used as a guideline in rock support design decisions. The classification is based on the rock block size (RQD/J_n), joint shear strength (J_r/J_a) and confining stress (J_w/SRF) (Barton, Lien and Lunde, 1974).

Where: RQD = Rock Quality Designation

J_n = joint set number

J_r = joint roughness number

J_a = joint alteration number

J_w = water reduction factor

SRF = stress reduction factor

2.5.2 Modified prime number

The modified prime number, N' is a modification of the stability number initially explored by Mathews et al. (1981). It is an alteration of the Q system where the stress reduction factor is not considered. Potvin (1988) introduced this parameter

to measure the rock mass ability to remain stable under given conditions. Three specific multiplying factors are applied to acknowledge the strength-to-stress effect, joint orientation and gravity (Zhang *et al.*, 2018) as shown in Equation 2.1.

$$N' = Q' \times A \times B \times C \qquad (2.1)$$

Where: N' = Modified prime number

Q' = Rock mass quality

A = Factor relating to strength to stress effect

B = Factor relating to joint orientation

C = Factor relating to gravity

2.5.3 Equivalent linear over-break/slough

Equivalent linear over-break/slough (ELOS) is a method of converting the volumetric cavity monitoring system (CMS) measurement into an average sloughage depth over the entire stope surface. It is the average over-break from a stope wall. Equation 2.2 calculates ELOS while Figure 2-8 and Figure 2-9 illustrate ELOS.

$$ELOS = \frac{(Volume\ of\ slough\ (overbreak)\ \ from\ stope\ surface)}{(Stope\ Height \times Wall\ Strike\ length)} \qquad (2.2)$$

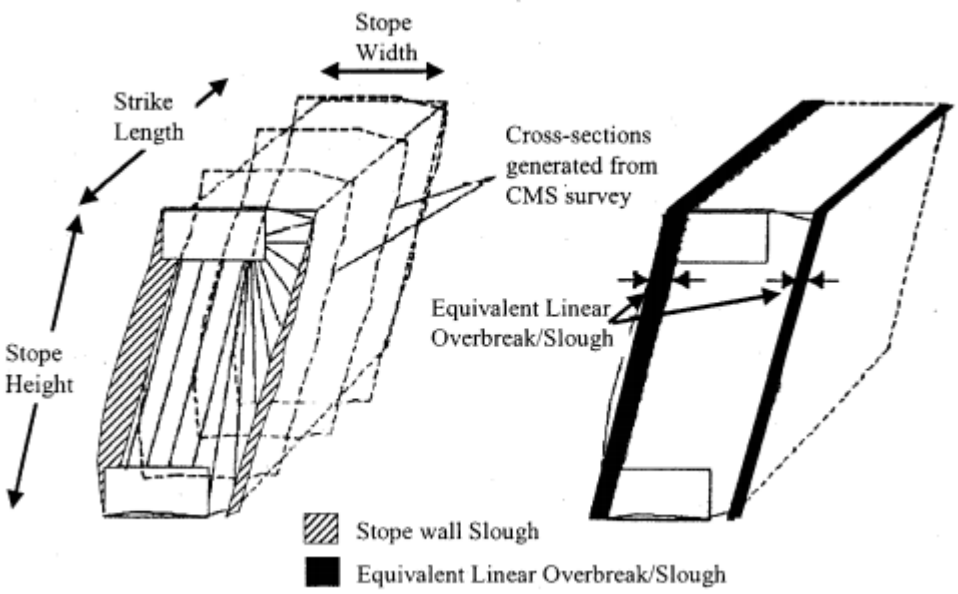


Figure 2-8: Schematic of ELOS (Clark & Pakalnis, 1997)

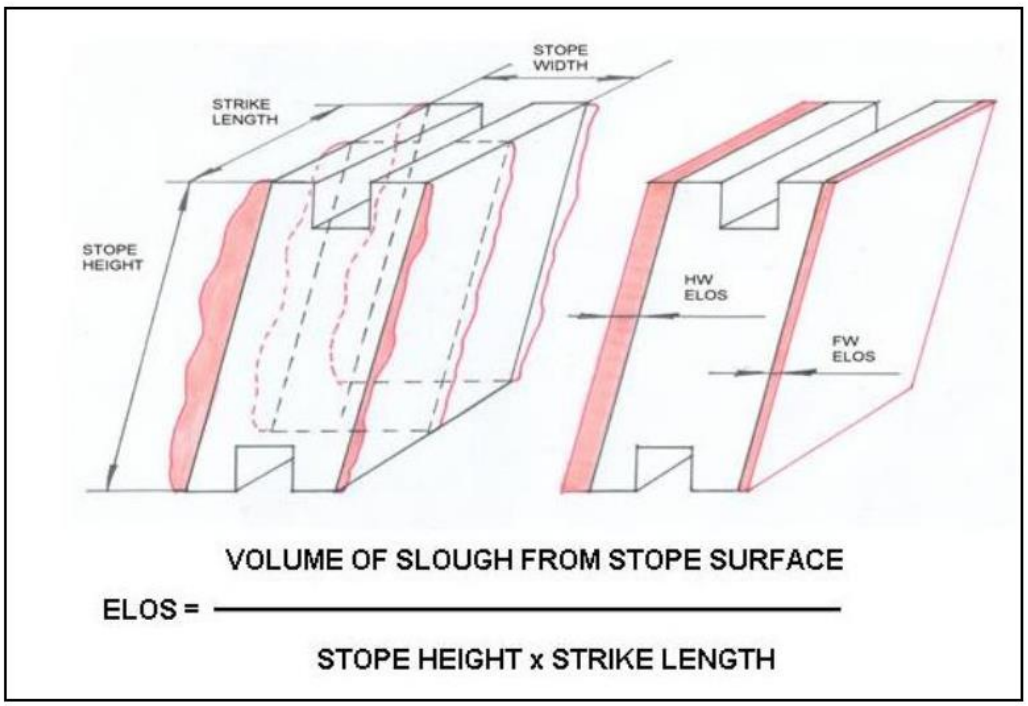


Figure 2-9: Concept of ELOS (Andrews and Barsanti, 2008)

Stope surfaces with huge excavation dimensions are more susceptible to high ELOS values. This problem is further exacerbated by the presence of faults and any other

geological features on the stope surfaces. Suorineni et al. (1999) concede that when a fault passes through a stope, its effect on the different stope surfaces may be considered separately. This allows for over-break planning on individual stope surfaces and aids stope stability efforts.

The advantage of calculating ELOS is that its meaning in terms of unplanned over-break is apparent and sources of unplanned over-break can be associated with the individual stope walls (Henning, 2007). This parameter is important in establishing stability limits for underground mines.

2.5.4 Hydraulic radius

Hydraulic radius (HR) is another parameter necessary for stability analysis. It is the measure of the extraction area of a stope surface where the stability of a given rock mass with certain geotechnical characteristics is estimated. Sewnun et al. (2018) express it as the ratio of the face area to the face perimeter as shown by Equation 2.3.

$$HR\ (m) = \frac{Area\ of\ surface\ analyzed\ (m^2)}{Perimeter\ of\ surface\ analyzed\ (m)} \qquad (2.3)$$

It is suited for two-dimensional rectangular surfaces and is based on boundary geometry. In principle, larger HRs on stope surfaces mean larger exposed areas and a subsequent decrease in stope stability. Stopes with large excavation dimensions normally exhibit high HR values and require additional support.

2.5.5 Stability graphs

Stability graphs combine information on rock mass and structure, stress around the opening, and the size, shape, and orientation of the opening to predict stope stability. They take cognisance of the stability index number, which indicates the rock mass resistance to given stress conditions, and HR, which represents the dimensions of the stope face (Mawdesley et al., 2001). Generally, the graphs show stable, unstable, and cave transition zones as shown in Figure 2-10. Figure 2-11 extracted from Suorineni (2010) shows how the increase in research from 1981 led to the evolution of stability graphs.

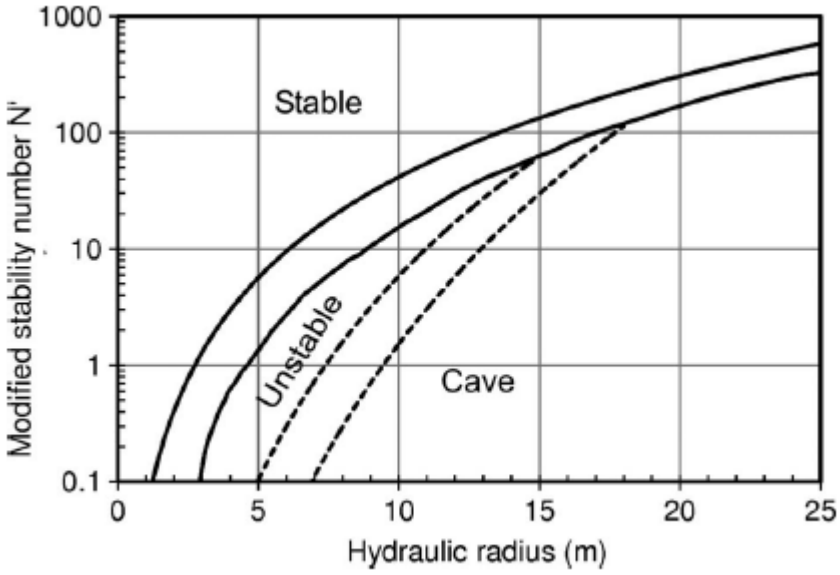


Figure 2-10: Standard stability graph (Suorineni, 2010)

Period	Developments
1980–1985	Introduction of stability graph : 26 case histories.
1985–1990	Calibration of stability graph factors and zones :175 cases.
1990–1995	Tentative cablebolt support line
	Re-definition of unstable/cave (supportable transition boundary – cablebolt support line)
	First partial statistical definition of stable/unstable zone
	Proposed dilution lines added to stability graph
1995–2000	Re-definition of the transition zones
	Modified gravity factor for sliding failure
	Second partial statistical definition of stable/unstable zones
	Introduction of RF
	Calibration of proposed dilution lines ELOS
	Modified gravity factor for footwalls with shallow dips $<70°$
	Proposed volumetric index
	First complete statistical analysis of stability graph using Baysian likelihood statistic
	Introduction of fault factor
	Modified stress factor to include tension and stress-dependent transition zones
2000–2005	Expanded database to ~400 cases and modified stability graph zones from Australian database
	Second complete statistical analysis using logistic regression: 483 case histories
	Time-dependent stability graph
2005 to date	Numerical modelling to validate the *B* factor

Figure 2-11: Chronology of modifications to the stability graph (Suorineni, 2010)

Suorineni (2010) points out that the stability graph database increased from 26 cases in 1981, to 175 cases in 1988 and over 483 cases in 2010. The reliability of these graphs depends on the size, quality, and consistency of the databases.

Suorineni (2010) further highlights that arbitrarily choosing between the original and modified stability number factors results in incomparable data that cannot be combined, while different transition zones result in different interpretations of the stope state of stability. It becomes important to set the type of stability graph one wants to use for assessing their stopes. Figure 2-12 shows some of the variations.

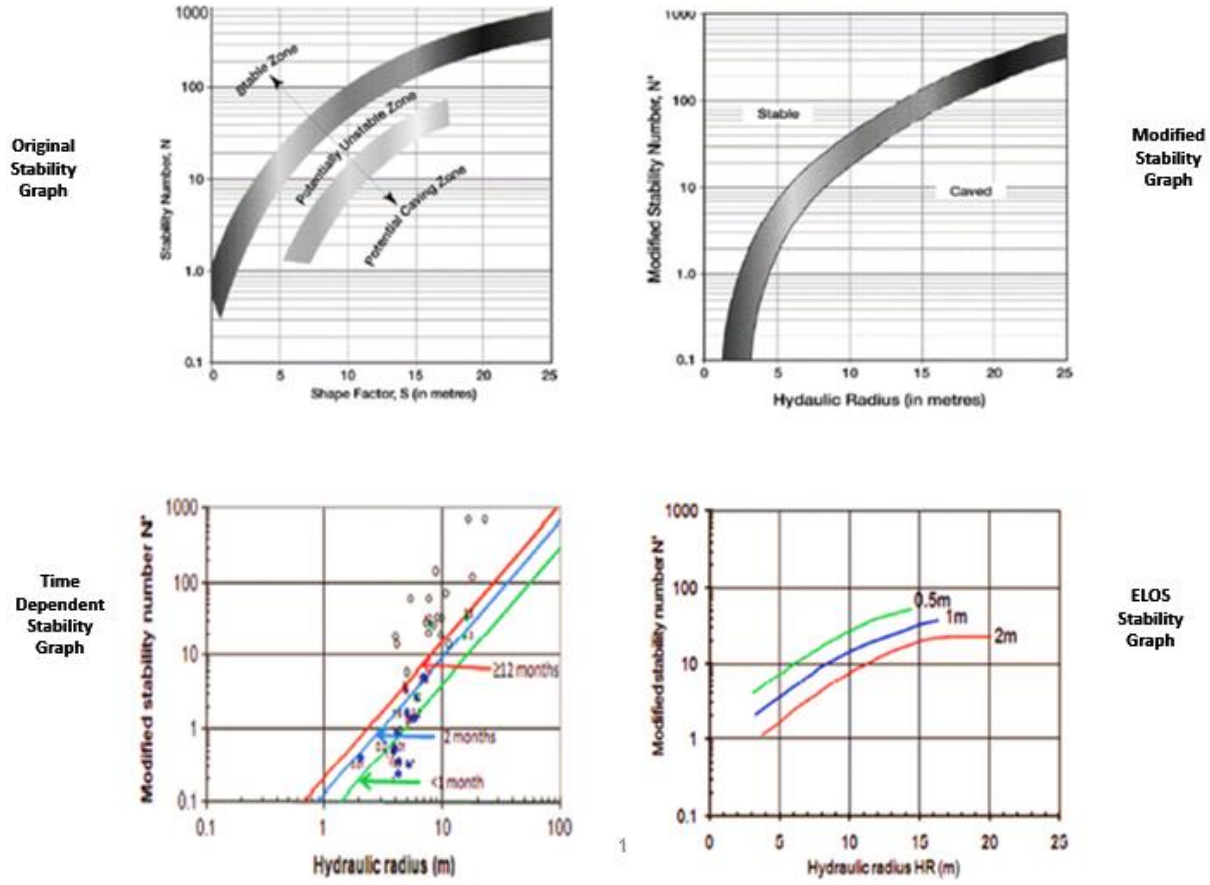


Figure 2-12: Types of stability graphs (Suorineni, 2010)

However, the stability graph methods by Potvin suffer some limitations in the way of applicability. Since they were developed from empirical data obtained from a few mines with specific geologies and rock types, they do not account for stability in unique geological environments as well as fully account for instability arising from the presence of faults, joints, and stress distribution. As an empirical derivative, the graphs are affected by the size, quality and consistency of the database (Suorineni etal., 2014).

Furthermore, the graphs are subjective in that their accuracy depends on the accuracy of input parameters such as rock quality designation and joint orientation. The graphs are only qualitative and stopes can only be described as stable, unstable, or caving (Papaioanou & Suorineni, 2015). They are open to different

interpretations owing to the different transition zones developed by different authors. Recognising the limitations in this form of stope stability assessment helps appreciate the graphs as guidelines and allows for the tandem application of other approaches to best assess stope stability.

2.6 Blast Hole Drilling

Initial stoping stages involve drilling holes into the rock mass. The drill/blast pattern determines where explosive charges for subsequent fragmentation will go. It is critical to understand the parameters discussed in Chapters 2.6.1 to 2.6.3 to achieve the best fragmentation (Hartman, 1992).

2.6.1 Blast hole diameter

In practice, the hole diameter is matched with the length of the holes required. Large-diameter holes accommodate more explosives allowing for wider spacing between holes and reducing the number of holes required. It reduces explosives costs (Hartman & Mutmansky, 2002). However, wide-spaced holes contribute to coarser fragmentation, which may be a challenge when loading equipment does not match the fragment size. This hinders ore from being loaded out of stopes and increases stope turnaround time. Ideally, the chosen hole diameter should strike a balance between the amount of required explosives and fragment size.

Since hole diameter also influences the stoping width, the desired diameter of the hole together with the hole length should be achieved at the end of drilling. All holes should be free from obstructions and closure to reduce instances of re-drilling and problems when charging.

2.6.2 Blast hole drilling pattern design

Ibarra et al. (1996), state that the designed drill pattern and the slot placement for an individual stope vary with the access available for drilling. For instance, primary stopes can be excavated with parallel blast holes and on/off centre raise bores while narrow access secondary stopes can be excavated with fan pattern blast holes and on/off centre raise bores. Other cases employ the same drilling pattern for both primary and secondary stopes (Ibarra et al., 1996). Figure 2-13 shows the primary stope design with parallel-drilled blast holes and the secondary stope design with fan-drilled blast holes.

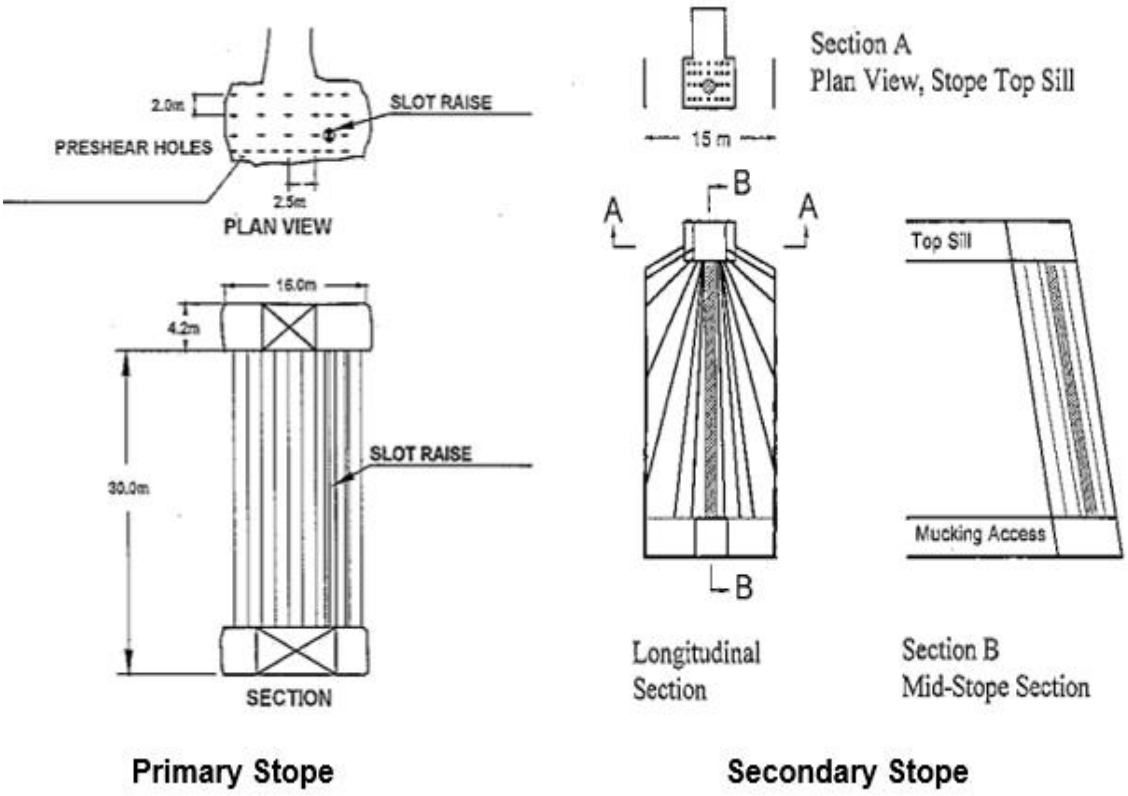


Figure 2-13: Primary and secondary stoping drilling patterns (Ibarra et al., 1996)

Drilling patterns aim to place holes where a minimal amount of explosives per volume of rock broken (powder factor) will be required for fragmentation. Desired

fragmentation results, normally uniform rock size distribution, inform the type of drilling pattern to be used. Uniform fragmentation results when exploding charges are within a particular distance from an exposed face of the rock mass.

In the process of fragmenting large rock masses, charges must be placed in a series of holes drilled in a way that the ones closest to the free face break and create new exposed faces. Chai et al. (2019), agree that this placement of holes and their angles within the drilling pattern is critical as it influences the quality of the resultant blast.

2.6.3 Blast hole drilling accuracy

Hartman (1992) raised the following factors as affecting the accuracy of drilling in stopes:

- Inaccurate placement of drilling reference marks;
- Incorrect drilling setup within stope;
- Drilling equipment limitations;
- Deviation from the standard procedure;
- Drilling equipment conditions;
- Inconsistent drilling operation; and
- Geological structure.

One or a combination of the factors listed may create a deviation from the intended drilling plan and cause poor fragmentation, leading to secondary blasting and/or making loading difficult. Drilling inaccuracies particularly in perimeter holes are detrimental as they change the stope boundaries causing problems of dilution, over-break, and/or under-break.

2.6.4 Drilling mechanical aspects

The success of drilling and its eventual implication on LHS performance hinges on attaining the correct and optimum operating characteristics of the drilling unit. Hustrulid (1971) notes that the efficiency of percussive rock drilling is of considerable significance to mining costs. The recommended values for air pressure, applied thrust, rotation speed, penetration rate, air consumption, blows per minute and drill steel revolutions per minute make up some of the critical parameters that should be followed for effective drilling.

Rapson and Rupprecht (2004) show that the use of large-diameter drill bits reduces the rotation of the drill steel, lowering the drilling and penetration rates. Under such conditions, a mismatch of the drill steel and drill beat could result in a compromise of the quality of the holes drilled.

2.6.5 Rock condition

The variation of rock conditions underground complicates the process of drilling with further caution required on sensitive ground to ensure accuracy and compliance are achieved. Fractured ground is generally hard to drill into as it slows down the penetration rate. Water is lost into the cracks, compromising drill bit cooling and lubrication. As a result, rods get stuck in holes, lengthening the drilling time. Fractured holes also close easily and require the insertion of poly pipes to keep them open after drilling and prevent instances of re-drilling. Brown et al (1981). also note that anisotropy in the mechanical properties of a rock can influence rock-bit interaction and cause the bit to deviate. Similar observations are made in mining environments with varying ground conditions.

2.7 Blasting

Excellent LHS fragmentation is critical for effective stope cleaning and excavation stability. Deviations from standard blasting practice can lead to bad breaks, directly affecting safety, dilution and output (Henning, 2007). An understanding of the blasting sequence and factors that influence blast vibration is critical to achieving excellent LHS fragmentation.

2.7.1 Blasting sequence

Heidarzadeh et al. (2018) highlighted a study that examined the sensitivity of hanging wall failure to the direction of excavation of a primary stope. One study finding was that the degree of stress-driven hanging wall failure is greater when the stopes have retreated from the direction of the principal major stress. Based on this finding, it becomes critical to avoid retreating stopes from the direction of principal major stress to reduce the likelihood of failure.

2.7.2 Blast vibration

When blasting, high-pressure explosive gas products penetrate along fractures in the directions around a blast hole. This release of energy causes vibrations in the surrounding rock mass and if the vibrations are strong enough, they may cause sloughing (Singh, 2018). The amount of vibration experienced depends on:

- Explosive product;
- Explosive density;
- Blasting pattern;
- Powder factor;
- Charge concentration;

- Charge confinement; and
- Delay timing.

2.8 Statistical Modelling

Davison (2008) defines a statistical model as a probability distribution constructed to enable inferences to be drawn or decisions to be made from data. It is a representation of observed data and represents the relationship between one or more random variables with other non-random variables. Davison and Forster (2010) are of the view that the application of statistical analysis to a particular data set is done to simplify reality, gain understanding, compare theories, predict future events/trends, and control processes among other things.

Within the mining industry, statistical models have been applied to facilitate design and decision-making. Over the years, researchers have shown the suitability of applying statistical models to solve mining problems. Hempkins (1969) showed the applicability of mathematical and statistical models for the prediction of ore distribution patterns in mines of the Witwatersrand basin.

More studies by Dahlberg and Griffiths (1967), Billaux et al. (1989), Pandey et al. (2011), Granian et al. (2015), Schafer (2018) and more recently Kenda et al. (2020), Hinz et al. (2020) and Feizi et al. (2021) have shown the wide suitability of statistical modelling and regression analysis in various mining fields. Their research covers aspects of hazard location, lithological analysis, grade variability, exploration drilling, occupational noise exposure, mine water level prediction, rock mass modelling, and mine pool formation.

The approaches used by these researchers are congruent with Davison's (2008) assertions that models should be consistent with knowledge of the system under study, extrapolate to related sets of data and if possible, have mathematical and statistical properties. They show that statistical models can be applied to predict outcomes where there is clear data on variables and their relationships can be modelled. The rationale can be justified in a vast range of domains and more so, in the prediction of relationships between LHS performance variables.

2.8.1 Statistical model accuracy metrics

The selection of an appropriate statistical model involves, in its simplest form, fitting candidate models on a training set, tuning them on the validation dataset, and selecting a model that performs best on the test dataset based on a selected metric. Brownlee (2018) adds that other approaches to selection involve resampling methods and probabilistic statistics. Regardless of the approach taken, the performance of any generated statistical model can be measured using metrics. These show how close the models are to representing or predicting reality.

Models are acceptable when metrics measure to reasonable limits. Authors including Yang (2003), Yuan et al (2005) Barrett (2012), Fabozzi et al. (2014), de Myttenaere et al. (2016), McAlevey & Stent (2017) and Henley et al. (2020) among others highlight the application of some model accuracy metrics in various fields. Their combined use aids in validating statistical model accuracy and since the principles are similar across different fields, they can be confidently applied in mining scenarios.

Coefficient of determination (R^2): It is the proportion of variance in the dependent variable that is predictable from the independent variable and measures the "usefulness" or "goodness" of a regression fit. Measured on a range from 0-1, an R^2 value close to zero indicates the difficulty associated with explaining a response variable based on a predictor variable, while an R^2 value close to one is desirable and shows how easily a response variable can be explained by a predictor variable. Barrett (2012) suggests that this metric should be accompanied by graphs and confidence intervals to provide a more complete evaluation of a regression equation.

Adjusted coefficient of determination (Adj R^2): This is a modified version of R^2 that adjusts the number of predictors in a regression model. This value provides a more precise view of correlation as it decreases when less significant variables are factored in.

F Statistic: This metric is used in statistical analysis to identify whether the means between two populations are significantly different or not. It is the ratio of two variances and accounts for corresponding degrees of freedom to estimate the population variance (Hessing, 2018).

Prob F statistic: It tells the overall significance of the regression and assesses the significance level of all variables put together. The metric depicts the probability of the null hypothesis being true. Low values imply that at least some of the regression parameters are nonzero and the regression equation possesses some validity in fitting the data.

Log likelihood: The parameter measures the goodness of fit of a model. The values can range from negative infinity to positive infinity, with generally higher values indicating a better fit. However, given the nature of the range of values possible, it may be misleading to take an absolute value and use it as an indication. Instead, several regression models are fitted to a dataset and their log likelihood is compared. The one with the highest value is chosen.

Akaike information criterion (AIC): AIC is used for model selection and penalises the errors made in case a new variable is added to the regression equation (Cavanaugh & Neath, 1999). The difference between the number of parameters and the likelihood of the overall model gives the AIC value. As an absolute value, the AIC is not important (Fabozzi *et al.*, 2014), but in model comparison, a model with the lowest AIC value offers the best fit.

Bayesian information criterion (BIC): The BIC is similar to the AIC in principle, but offers stiffer penalties for the addition of more variables. This makes the criteria favor more parsimonious models over complex ones. BIC is particularly better than AIC in multi-variate regression analysis as shown by Yang (2003) because of its ability to remain consistent in selecting the true model.

Kurtosis: This refers to the nature of distribution tails, that is, their length and weight (Bono *et al.*, 2019). In reviewing this metric, Balanda and Macgillivray (1988) conclude that kurtosis is a component of distributional shape where probability moves (location and scale-free) from the shoulders of a distribution to its center and tails. Computing kurtosis determines how many outliers exist in a

standard normal distribution. Datasets with high kurtosis normally have heavy tails or outliers while those with low kurtosis have low tails or fewer outliers.

Skewness: Bono et al. (2019) express this metric as the degree of asymmetry of a distribution, showing how much the distribution is biased to either the left or the right. A perfectly symmetrical dataset with a normal distribution possesses a skewness of zero.

Covariance: Covariance assists with quantifying relationships between multiple random variables. Taylor (2023) adds that the metric evaluates the extent to which variables change together. A positive covariance indicates that variables tend to vary in the same direction while a negative one shows that they vary in opposite directions.

Standard error: It measures the accuracy with which a sample distribution represents a population by using a standard deviation (Kenton, 2022). The metric represents the difference between the derived mean of the population and a known mean, or one accepted as true. The value tends to be smaller with the inclusion of more clustered means in the calculation (Andrade, 2020).

2.8.2 Multi-variate analysis

Multi-variate regression is a technique used to measure the degree to which the various independent variables and various dependent variables are linearly related to each other. It comes into play when there is more than one independent variable and simple linear regression does not work. It works well in understanding the relationships among variables in the dataset.

The stepwise process of multi-variate regression analysis includes feature selection and feature engineering, normalising the features, selecting the loss function and hypothesis, setting hypothesis parameters, minimising the loss function, testing the hypothesis, and generating the regression model.

3 METHODOLOGY

The empirical approach to LHS performance investigation involved the analysis of three factors and their contribution to under-break and over-break. The chapter shows how observations and secondary data analysis were used to achieve the objectives of the project. It further highlights the challenges faced in data collection and analysis. Quantitative methods were supplemented with qualitative ones to gain further insights.

To answer the research questions, the research adopted a stepwise process of categorising mining environments, analysing stope data files, developing predictive models, informing excavation design, and finally reviewing drilling and blasting practices as shown in Figure 3-1. These steps helped in leveraging the intersection that exists between geological environments, technical design aspects as well as operating tactics at the mine.

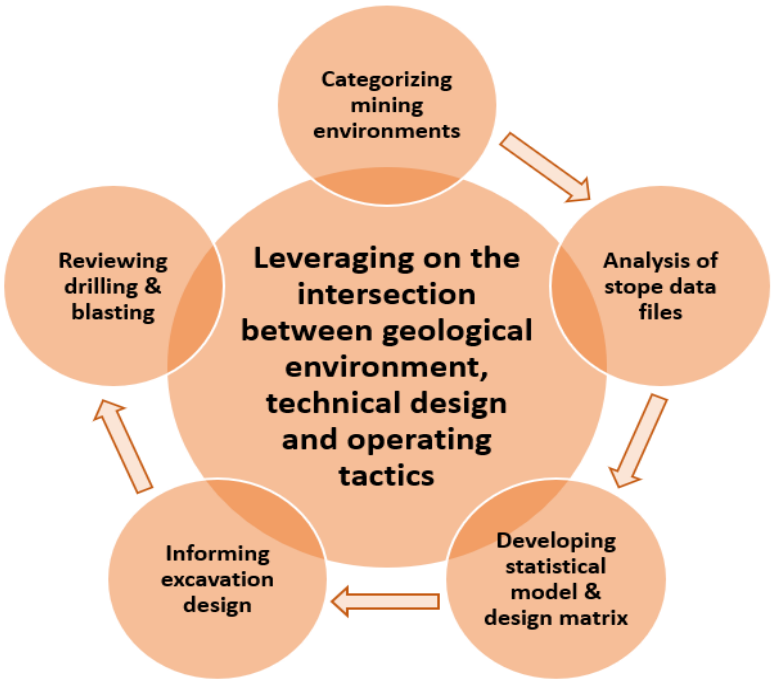


Figure 3-1: Research methodology

3.1 Categorising Mining Environments

In creating a comprehensive stope database, stope reconciliation on Deswik software was done for 60 stopes mined between January 2018 and April 2022. The rigorous exercise involved tracing completed LHS files and extracting relevant data to categorise the mining environments. This was in line with Henning's (2007) approach of establishing exhaustive stope databases for analysis by considering stope construction details (including drilling and blast design), stope excavation details, stope sequencing, geology, and rock mass structures as well as stress environments.

3.2 Analysing Stope Data Files

The first attempt at analysing stope data involved using mXrap (Harris & Wesseloo, 2015), a geotechnical data analysis and monitoring software that was on trial at the mine. The technicalities around the software and its application at the mine rendered it useless for solving the problem. It was discontinued as it did not provide progress. Subsequent work was carried out on Deswik software (White et al., 2008) and the results were extracted to Microsoft (MS) Excel (Microsoft Corporation, 2021) where exploratory data analysis was used to identify and investigate patterns and trends in the stope data, discover anomalies, test hypotheses, and check assumptions. The MS Excel database was complemented by stope health data as well as data from LHS physical files kept at the mine.

The next phase involved a geological block model exercise where LHS files were mapped onto geological blocks containing reef horizons. This was to establish the intersection of geological structures and stopes and identify areas of bad break influenced by geological structures. Planned (blue outline) and final (red outline) LHS profiles as shown in Figure 3-2 were imposed on geological block models with reef horizons (Figure 3-3). Filters were applied onto the reef horizons to remain with those influencing any breaking outside of the plan as illustrated in Figure 3-4. While the impact of geological complexities on LHS performance has been discussed in Chapter 2.2.3, the study found it fit to explore in depth the impact of reef horizons on LHS performance due to their uniqueness to the South Deep Gold Mine.



Figure 3-2: LHS cross-section before reef horizon mapping (LHS data files, 2022)

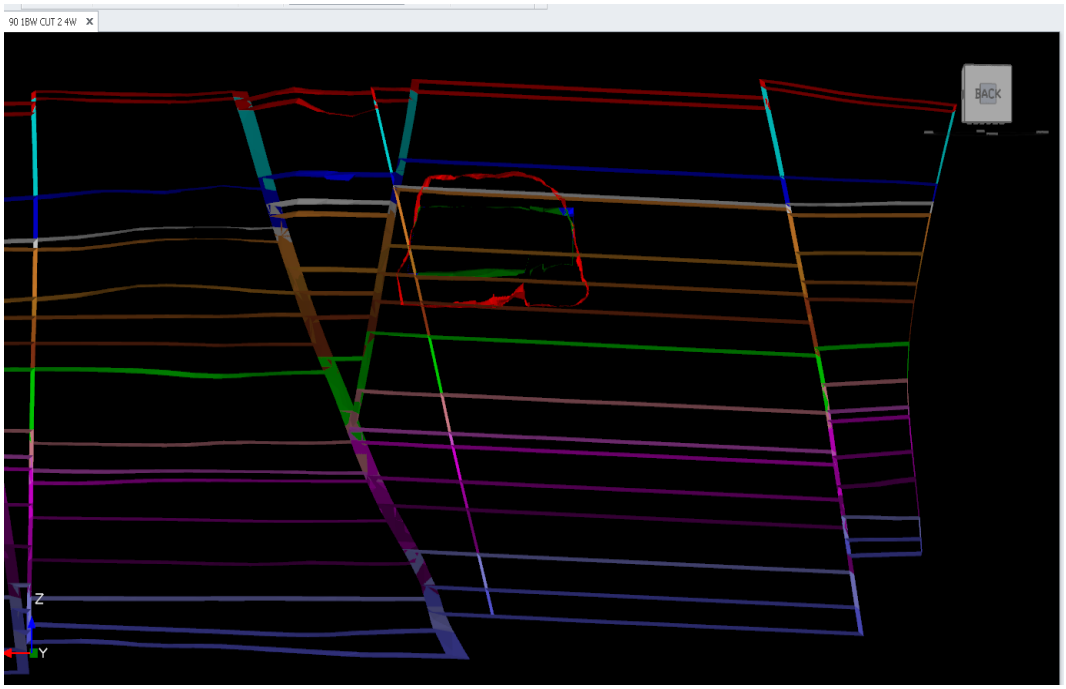


Figure 3-3: LHS cross-section after reef horizon mapping (LHS data files, 2022)

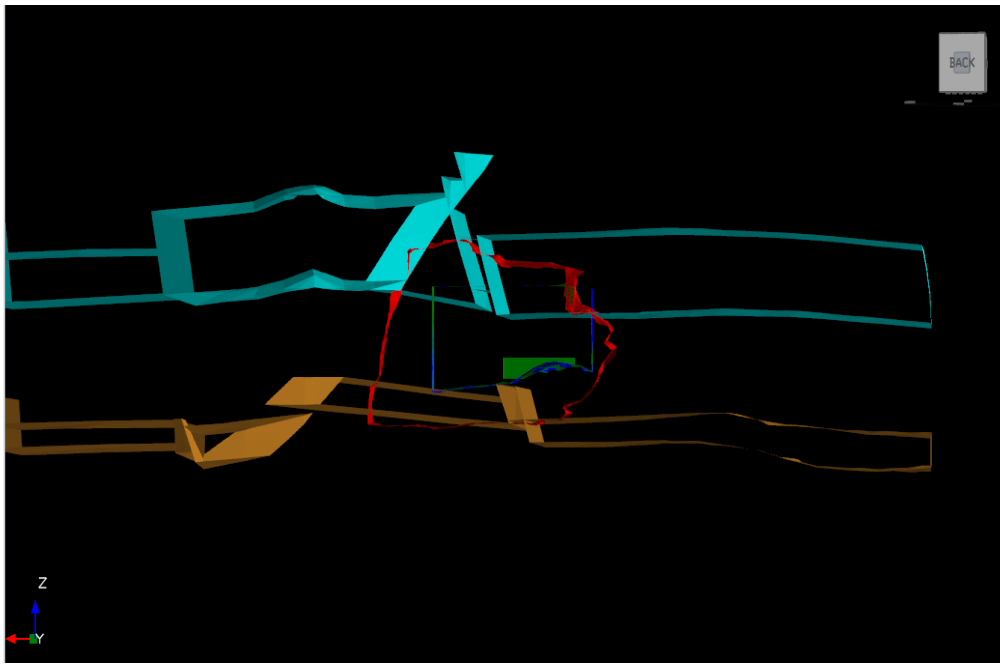


Figure 3-4: LHS cross-section after filtering (LHS data files, 2022)

3.3 Developing a Statistical Model and Matrix

To come up with an appropriate model that predicts the amount of over-break or under-break given stope excavation dimensions, the study initially considered

fuzzy data and clustering analysis approaches. However, considering the distribution of the data, a multi-variate regression approach was considered for creating a predictive model.

Statistical analysis was applied to the data using multi-variate analysis run on Python (Python Software Foundation, 2022). The analysis produced heatmaps, scatter matrices, and residuals which were then used to create a model that predicts over-break and under-break given the hydraulic radius. The model accuracy metrics explained in Chapter 2.8.1 solidify the case for the application of a multi-variate model on the data. Stope performance proportions and severities were standardised to formulate a matrix that predicts the levels of control for managing over-break given the combined effect of mining sequence, geologic environment, and reef horizons.

3.4 Informing Excavation Design

To inform excavation design, the study adopted an approach of analysing the relationship between LHS performance and stope mining sequence as well as that between LHS performance and stope boundary geometry. For the former, it explored the proportions of over-break and under-break attributed to primary, secondary, and sequential stopes while for the latter it explored the contribution of HR to over-break and under-break. These insights, coupled with observations from underground visits were used to come up with recommendations for improving excavation design.

3.5 Reviewing Drilling and Blasting

The limitation in number of underground visits afforded and the active drilling and blasting observations at the mine favor a more qualitative approach to LHS performance evaluation as compared to quantitative. To analyse performance, the study relied on underground observations, stope health files, quality control and quality assurance (QAQC) observation sheets, drilling returns and reports as well as charging returns and reports. Deviations from standard practice were recorded together with their contribution to poor LHS performance. The results were then used to formulate recommendations for improving drilling and blasting at the mine.

3.6 Challenges in Data Collection and Analysis

The major obstacle in data collection was getting access to the mine and mine data. Bureaucracies initially around Covid-19 restrictions and later mine underground access threatened the success of this study. However, working remotely with a mine supervisor helped cover this gap until physical access to the mine was granted.

Furthermore, the general perception of most operators underground during observations appeared to be that of regarding the researcher as a fault finder as reflected in conversations. This was cleared with time and a common understanding was reached where the intention of gaining insight and understanding of the mine processes was cemented.

Data collection was also a challenge in that there was poor stope reconciliation for mined stopes between 2018 and 2021. Some records were missing and had not

been captured accurately, thus, the inconsistency in data capturing created extra work for the study. Extra verification work with the QAQC department covered the gaps and qualitative analysis was done where the data was insufficient to support quantitative analysis.

The first attempt at categorising mining environments and analysing stope data files involved the use of software (mXrap) (Harris & Wesseloo, 2015) on trial at the mine. This was a futile exercise and Deswik was adopted for the task. For the creation of the predictive model, initial data indications showed that fuzzy data and clustering analysis would be suitable, but further sorting of the data later favoured Multi-variate analysis due to reduced complexity in computation.

4 RESULTS AND ANALYSIS

This chapter presents and discusses the findings from the data gathered over the research period. The type of data accumulated is structured to enable the answering of research questions, testing the research hypothesis, and achieving the research objectives. It further shows how the data relates to existing literature and how conclusions have been drawn from the intersection between what is ‘on the ground’ and what exists in the literature. The results herein are presented in quantitative means and backed by qualitative observations.

4.1 Data Gathered

4.1.1 Accuracy of measurements (Data QAQC)

The results are derived from a statistically significant database; however, data from additional stopes could improve the confidence and reliability of their use. The results from South Deep Gold Mine could be used in mines with similar geology and mining conditions.

The majority of the data was retrieved from Deswik Software, while the remainder was reconciled from physical LHS files. To reduce the margin of error in data collection, analysis, and overall treatment, only data signed off by the QAQC department and the rock engineering department was considered.

4.1.2 LHS Reconciliation

The first and crucial stage involved the reconciliation of 60 completed stopes mined between 2018 and 2022 and classifying them into different environments. The scatter plots in Chapter 4.2 are generated from Appendix A and Appendix B. They

give a summary of the performance of the stopes as well as stope surfaces looking at the relationship between hydraulic radius and over-break / under-break.

4.1.3 Supporting Files

To complement the reconciliation data, insights were further sought from other existing documentation at the mine. This included but was not limited to drilling returns and reports, charging returns and reports, drilling, and charging observation sheets as well as stope health reports. Stope health reports are monthly reviews summarising LHS performance based on drilling, blasting and hauling metrics. They provide a comparison of planned and achieved targets for each stope. It is however important to note that not all of the documentation was available for the initial 60 reconciled stopes. This made way for a more qualitative analysis that established trends in the operational culture at the mine.

4.2 Data Analysis and Discussion

Data was analysed based on each of the three factors corresponding to the research questions. The analysis adopted an approach similar to that used in risk assessment within the engineering field where the assessment matrix considers the likelihood (probability) and the potential impact (severity) of a hazard

In this context, the analysis of LHS performance considered the proportion of the over-broken / under-broken stopes as well as the extent to which the stopes were broken (severity). Proportion is a fraction a subset of stopes occupies relative to the whole set of stopes while severity reflects the extent of over-break / under-break to a stope, an insight into the quality of stoping. The combination of

proportion and severity analysis provided a nuanced view of LHS performance that incorporated both quantitative and qualitative aspects respectively.

4.2.1 LHS performance and geological environments

According to the standards set at South Deep Gold Mine, any stope over-break or under-break beyond 30% is considered undesirable. The relationship between LHS performance and geological environments was analysed using this rationale as simplified in Equation 4.1.

$$f(x) = \begin{pmatrix} Underbreak, x < -30\% \\ Desired, -30\% \leq x \leq 30\% \\ Overbreak, x > 30\% \end{pmatrix} \quad (4.1)$$

where f(x) is the stope performance classification as defined in Chapter 2.3 and (x) is the percentage excess/deficit amount from the planned stope fragmentation.

In analysing the effect of geological environments on LHS performance, the research considered the unique mining environments where stopes are located, the geological block models containing reef horizons where stopes are situated as well as the individual stope surfaces for further understanding of the location of the over/under-break. Figure 4-1 shows the overall performance of the stopes reconciled and analysed in this study.

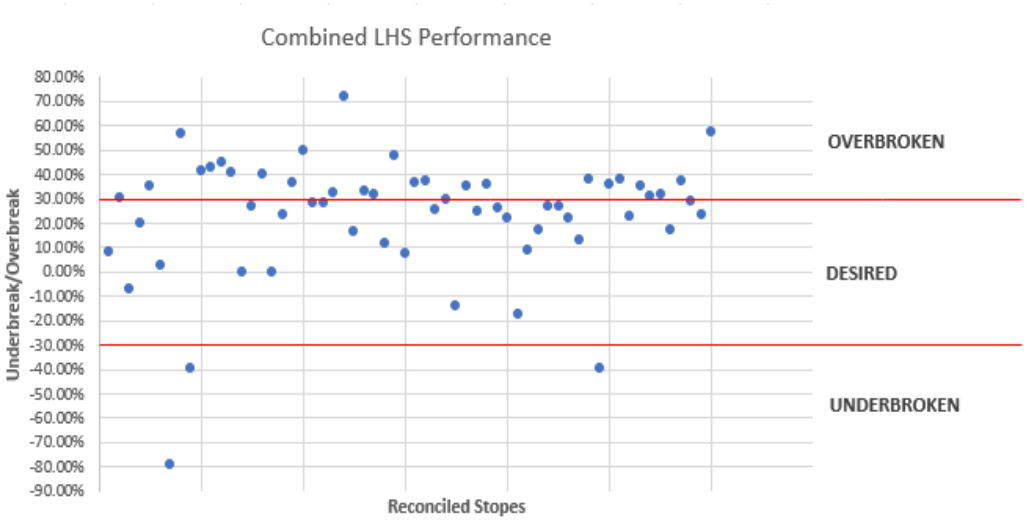


Figure 4-1: Overall LHS performance

Following the classification made in Equation 4.1, the results indicate that of the analysed stopes, 48.3% were over-broken, 46.7% desired, and 5% under-broken. This represents 53.3% of undesired stope performances in the analysis, a figure that is substantial for analysing and predicting the performance of over-break to a greater extent and under-break to a lesser extent.

A. Mining environments

Figures 4-2 to 4-7 illustrate the performance of LHS based on the unique mining environments while Table 4-1 summarises these findings. The performance of stopes in each of the unique environments was also subjected to the classification made in Equation 4.1.

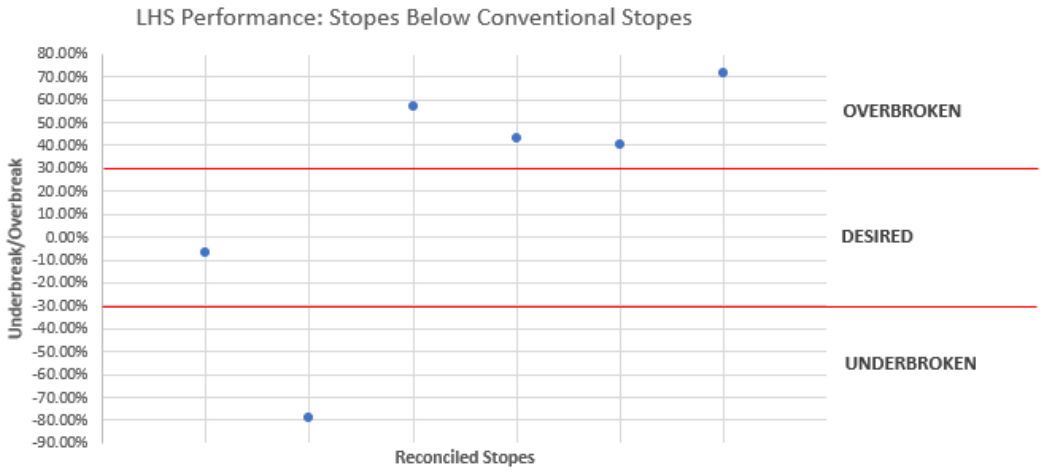


Figure 4-2: Stopes below conventional stopes

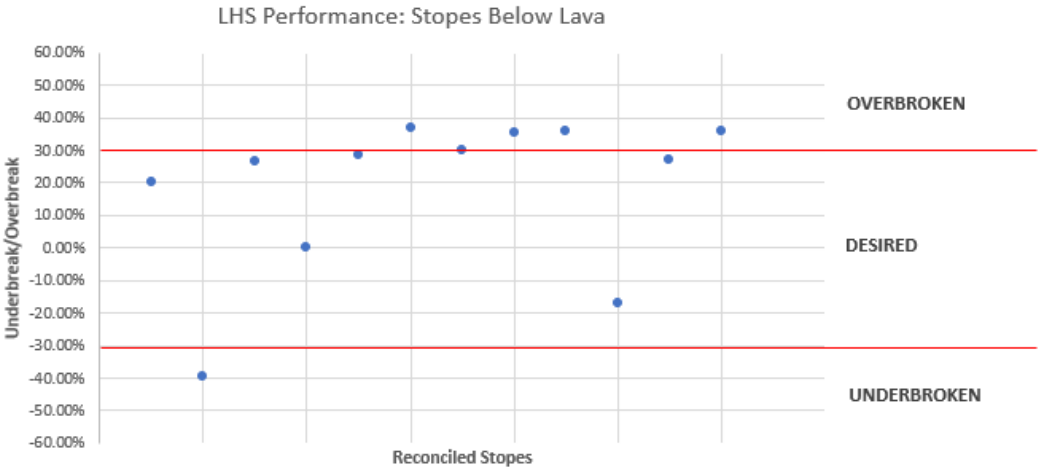


Figure 4-3: Stopes below lava

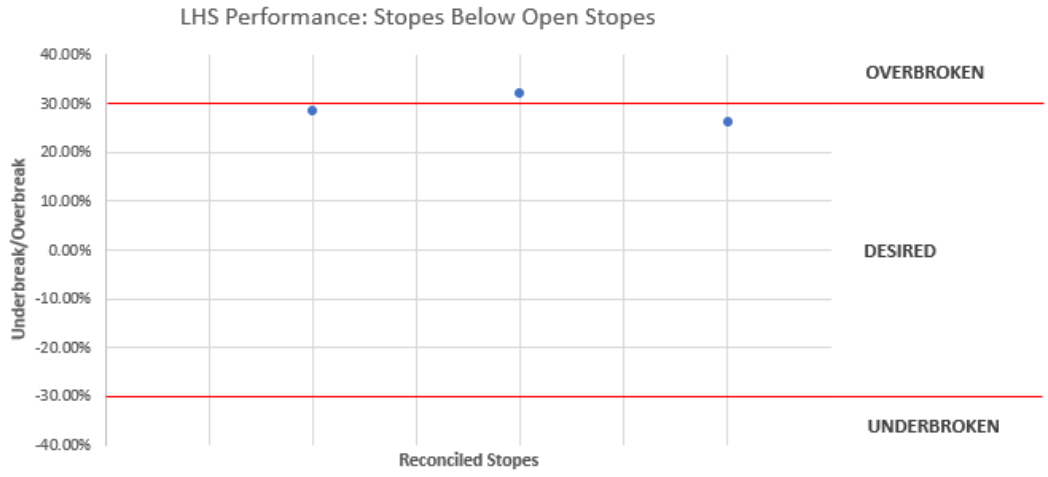


Figure 4-4: Stopes below open stopes



Figure 4-5: Stopes below open developments

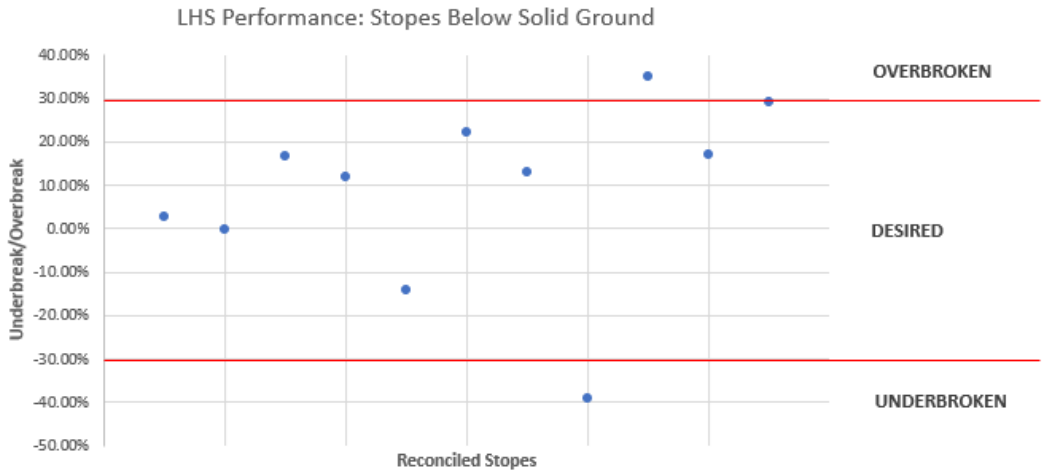


Figure 4-6: Stopes below solid ground



Figure 4-7: Stopes below de-stress cut environments

Table 4-1: LHS performance by mining environment

Stope Above	Over-break %		Desirable %		Under-break %	
	Proportion	Severity	Proportion	Severity	Proportion	Severity
Combined	48	39.93	47	15.79	5	-52.60
De-stress Cut	68	39.65	32	19.13	0	N/A
Conventional Stope	67	52.97	17	-7.20	17	-78.95
Lava	50	34.88	42	17.04	8	-39.61
Open Stope	33	32.06	67	27.27	0	N/A
Open Development	33	34.88	67	19.46	0	N/A
Solid Ground	9	35.21	82	10.87	9	-39.23

The performance of stopes is assessed based on the proportion and severity recorded on the three classes of stope performance (over-broken, desired, and under-broken). Generally, stopes existing under open stope, open development, and solid environments yield higher compliance standards as compared to the ones in de-stress cut, conventional stope, and lava environments. The undesired stope performances are prevalent in the latter environments, an initial indication that more attention should be given to them in designing stopes.

Figures 4-8 to 4-13 show the proportions as well as severities of the LHS performances based on the mining environments. They take cognizance of the mining environment proportions and severities within each of the stope performance classes.

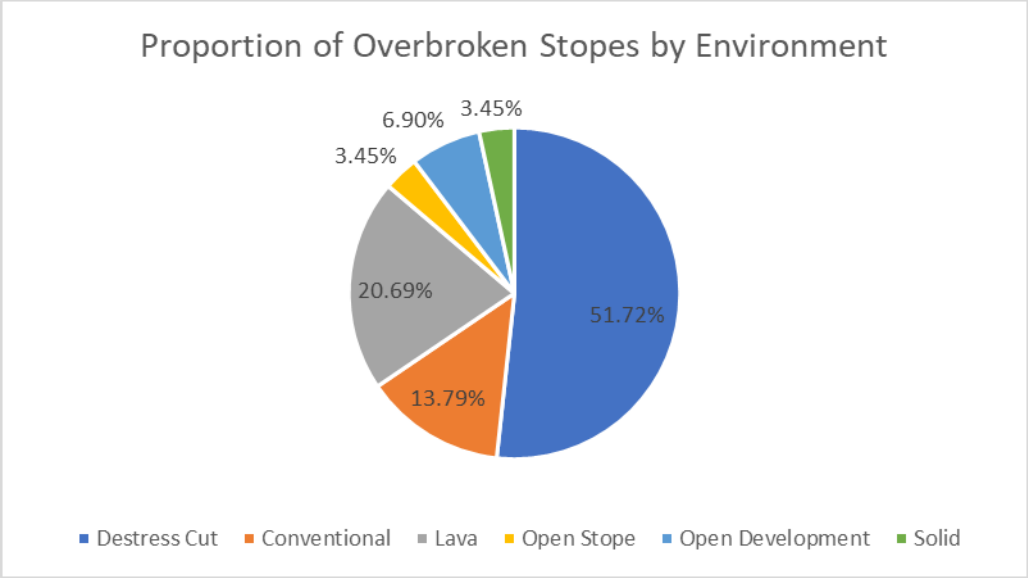


Figure 4-8: Proportion of over-broken stopes by environment

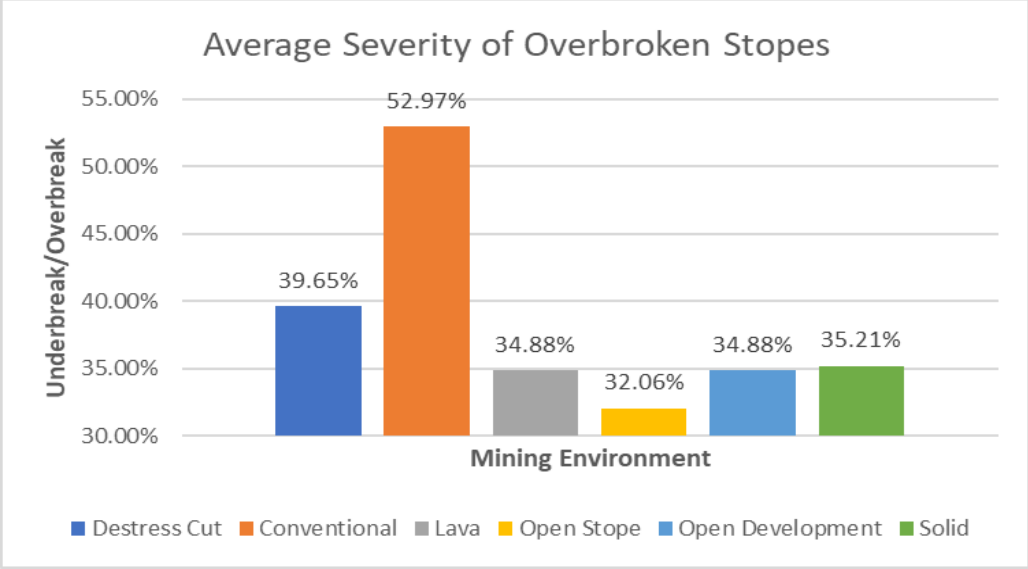


Figure 4-9: Severity of over-broken stopes by environment

The vast majority (86.2%) of the over-broken stopes is attributed to the de-stress cut, conventional stope, and lava environments. This follows that when you drill and blast into lava, the structurally weak nature of the lava makes it collapse thereby increasing the intended excavation dimensions which constitutes unwanted over-break. The over-break occurring in stopes below de-stress cut environments is attributed to the release of remnant energy along de-stress cut boundaries. Severe fracturing adds to over-break in Conventional stopes that were not tightly backfilled as the unconsolidated material falls off with the blast.

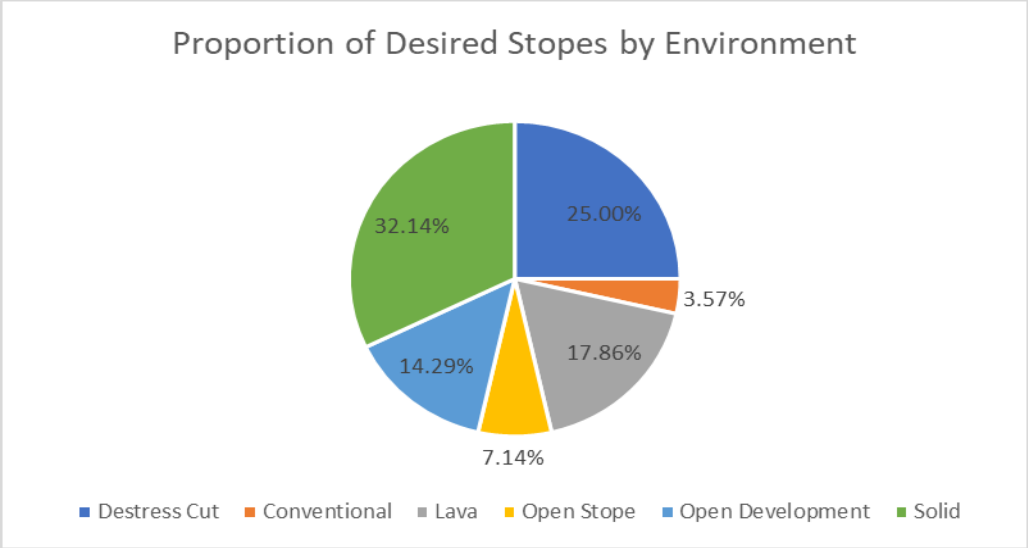


Figure 4-10: Proportion of desired stopes by environment

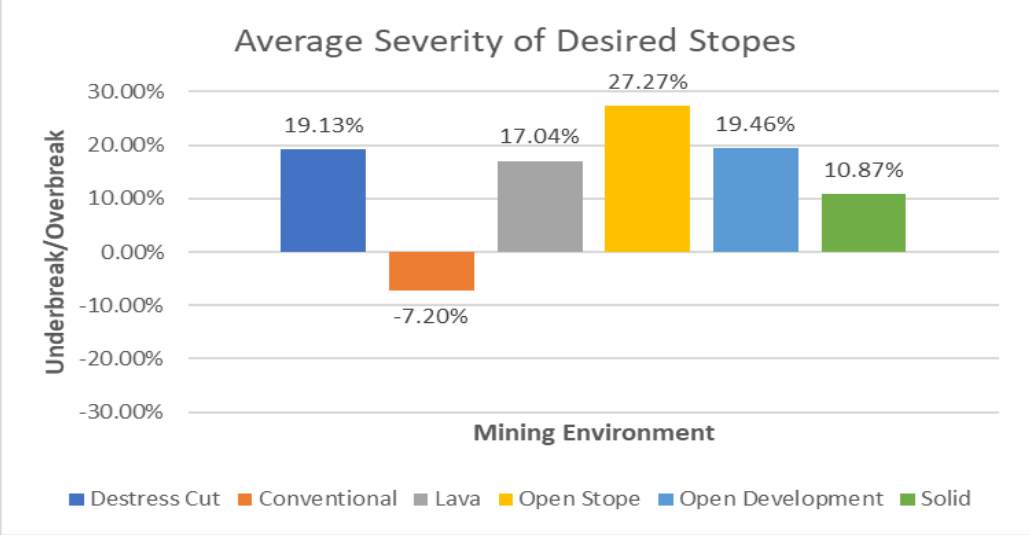


Figure 4-11: Severity of desired stopes by environment

The competent solid ground above stopes holds strong and does not fall off causing undesired over-break because it is geologically undisturbed. This explains why the greatest proportion and severity of desired stopes by environment comes from stopes with solids above as shown in Figure 4-10 and Figure 4-11. Furthermore, of the stopes with solids above, about 82% of them fall within the desired range with a severity of just over 10% as shown in Table 4-1. Stopes with open developments and open stopes above also comply with LHS performance contributing over 21% of the desired fragmentation. This is because the environments above are mined out cavities and there is no excess material to break.

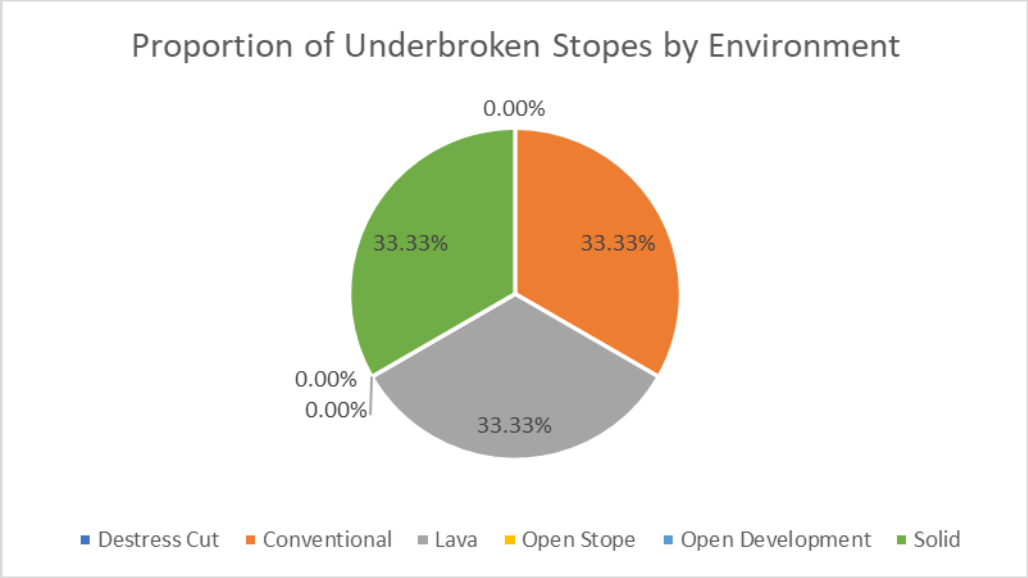


Figure 4-12: Proportion of under-broken stopes by environment

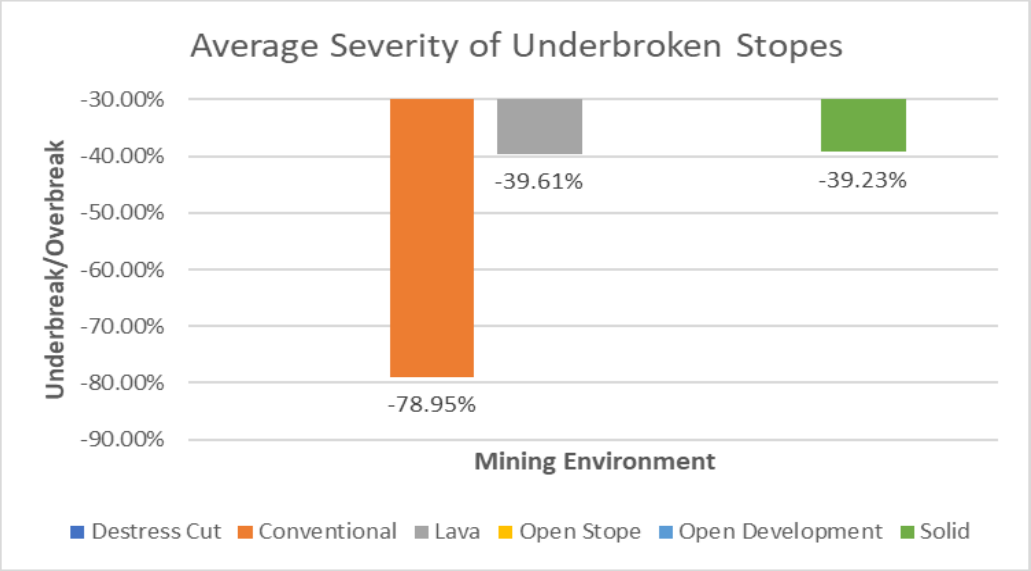


Figure 4-13: Severity of under-broken stopes by environment

The reconciled stopes give little indication of under-break patterns. However, the under-break occurring in stopes below solids points to the competent nature of the overlaying rock structure that becomes resistant and under-broken if proper drilling and blasting practices are not followed. Practice and observations at the mine show that drill operators have to avoid drilling into lava to reduce dilution and over-break. Holes are diverted and made shorter than initially planned. The under-broken lava stopes could be a result of changes in drilling parameters once lava has been intercepted to avoid the more detrimental over-break. The large under-break (-78.95%) under the conventional stope environment is treated as an outlier due to its uniqueness. De-stress cut, open stope, and open development environments do not have under-broken stopes as indicated in their performances above.

B. Reef horizons

It was found that reef horizons discussed in Chapter 1.1.2 have a contribution to LHS performance and their individual contributions are illustrated in Appendix D.

Figures 4-14 to 4-16 summarise the contributions of the reef horizons to LHS performance.

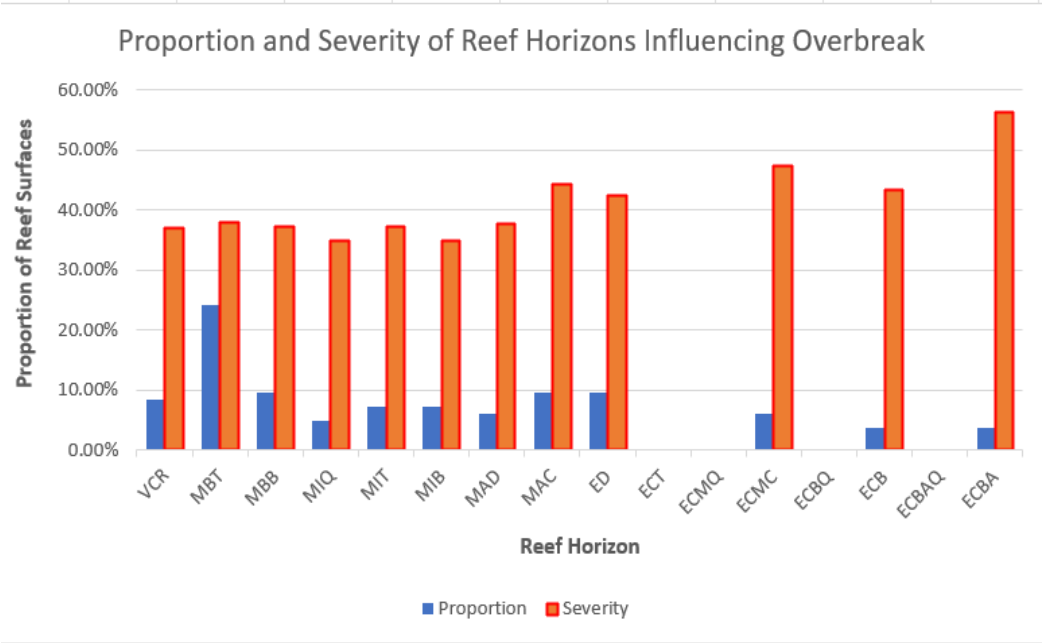


Figure 4-14: Proportion and severity of reef horizons influencing over-break

Five of the 16 reef horizons (MBT, MBB, MAC, ED, and VCR) account for over 60% of the over-broken stopes with relatively high severities (≈40%). The combined effect of their proportions and severity increases their likelihood of influencing over-break. ECMC and ECBA reef horizons have extremely high severities despite occurring in low proportions. As such, their impact on over-break is reduced. Stopes intersected by ECT, ECMQ, ECBQ, and ECBAQ reef horizons experienced no over-break, thus eliminating their possibility to highly influence over-break. It is however important to note that the likelihood of over-break increases when several reef horizons are compounded and within proximity of stope boundaries.

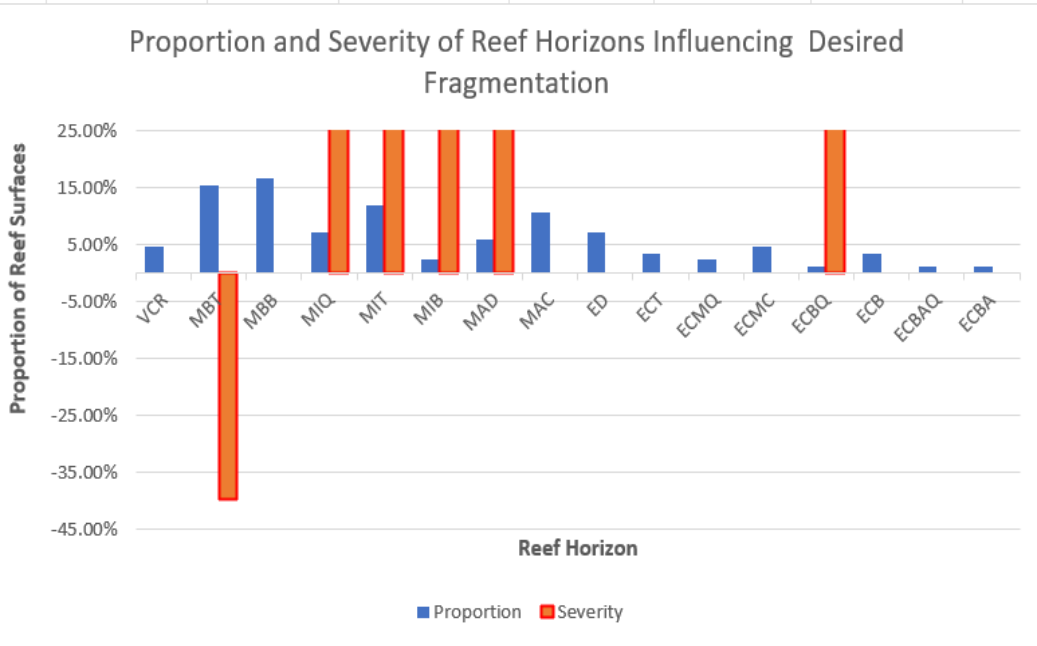


Figure 4-15: Proportion and severity of reef horizons influencing desired fragmentation

Within the desired range, MIB reef horizons affect performance differently from other reef horizons as shown by the plunge in Figure 4-15. All reef horizons intersect the complying stopes and their impact within these stopes is neglected because the stopes neither over-broke nor under-broke. The addition of more stopes for reconciliation could provide new insights into the behaviour of ECBA, ECBQ, and ECBAQ reef horizons as their severities seem to approach stope performance class boundaries.

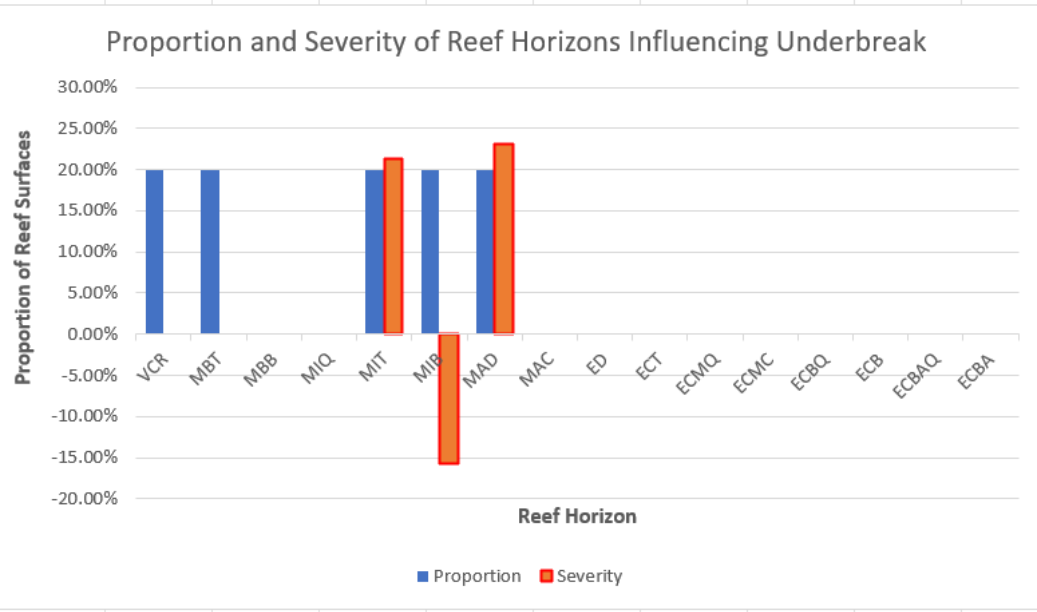


Figure 4-16: Proportion and severity of reef horizons influencing under-break

MBT, VCR, MIT, MIB, and MAD reef horizons contribute to the under-breaking of stopes. However, it is important to note that this is derived from only two stopes, which may be misleading as the under-break could be attributed to drill and blast factors. The reconciliation of more under-broken stopes could shift the trend quite significantly.

C. Stope surfaces

Above the impact of geological environments and reef horizons on LHS performance, the study further analysed the performance of individual stope surfaces. This analysis was important to establish the location and prevalence of over-break and under-break as well as ensuring that stope surface values (over-break and under-break) do not cancel each other out and provide the impression that there is no over-break or under-break within a stope.

The over-break and under-break on individual stope surfaces contribute to the overall stope performance and for that reason, the study considered a 10% limit

for stope surface over-break and under-break analysis, an approach simplified by Equation 4.2:

$$f(x) = \begin{pmatrix} Underbreak, x < -10\% \\ Desired, -10\% \leq x \leq 10\% \\ Overbreak, x > 10\% \end{pmatrix} \quad (4.2)$$

where f(x) is the stope performance classification and (x) is the percentage excess/deficit amount from the planned stope surface fragmentation.

Table 4-2 shows the stope surface performances while Figures 4-17 to 4-21 show the relationship between the individual stope surfaces and LHS performance.

Table 4-2: Stope surface performance

Stope Surface	**Over-break %**	**Desirable %**	**Under-break %**
Crowns	7	91	2
Hanging walls	68	25	7
Footwalls	54	37	7
Sidewalls 1	0	100	0
Sidewalls 2	0	100	0

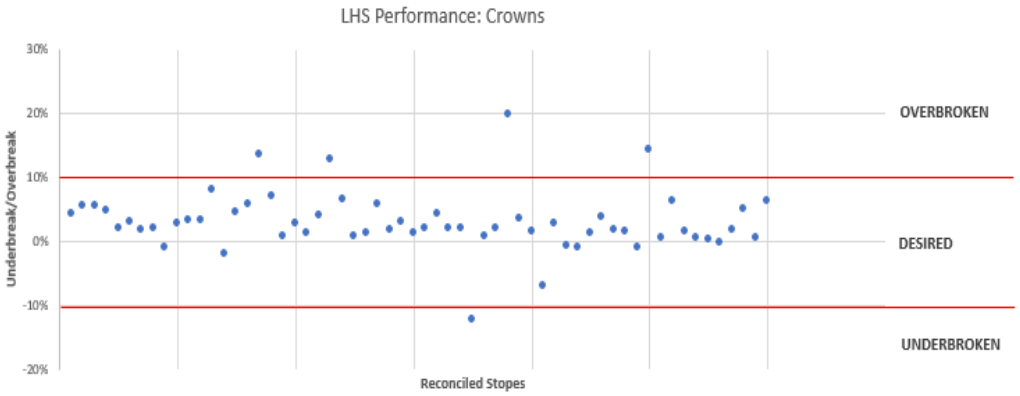


Figure 4-17: LHS performance and crowns

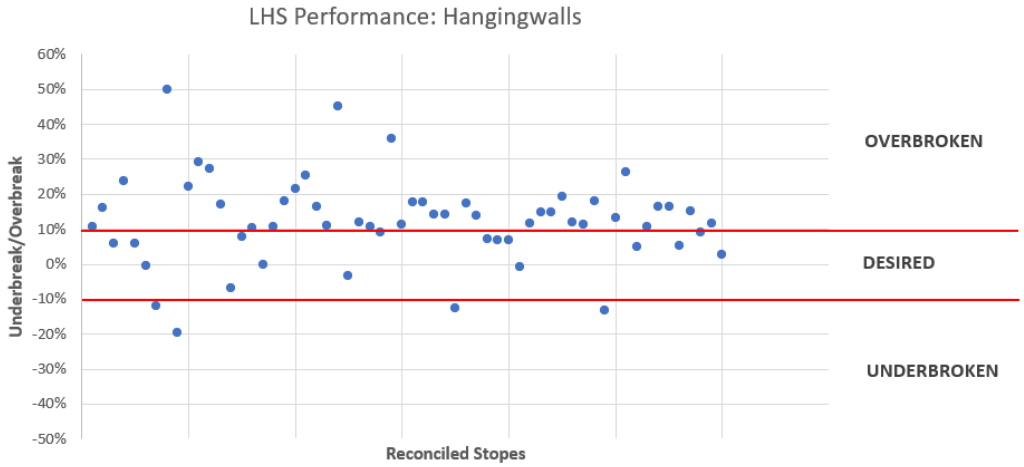


Figure 4-18: LHS performance and hanging walls

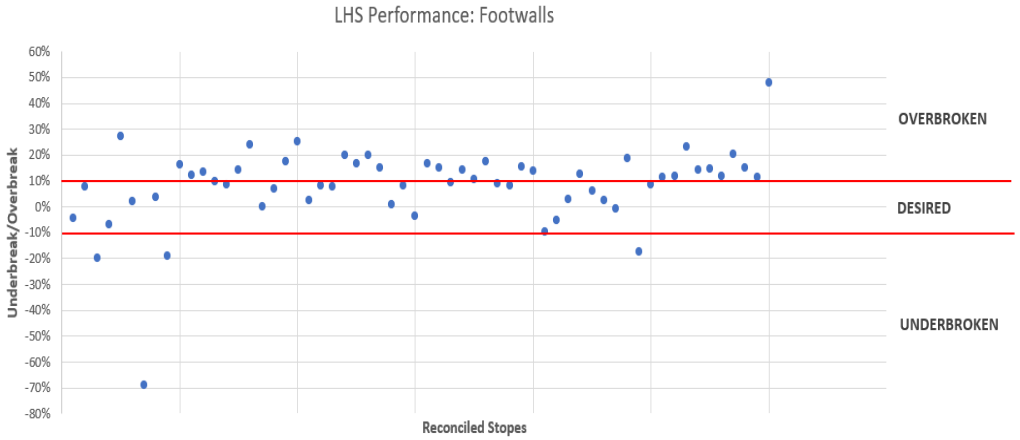


Figure 4-19: LHS performance and footwalls

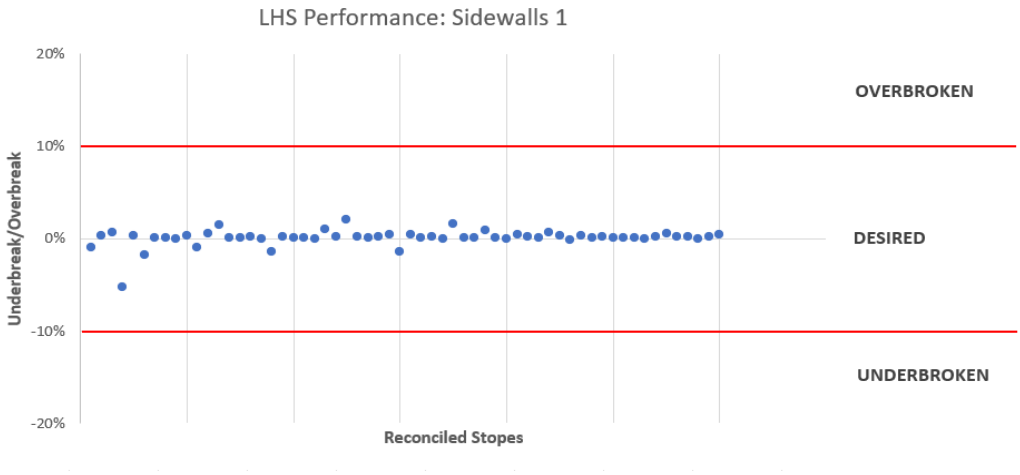


Figure 4-20: LHS performance and sidewalls 1

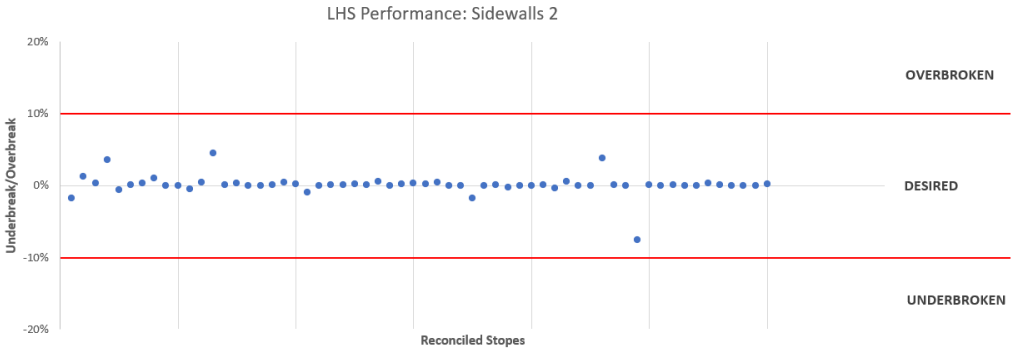


Figure 4-21: LHS performance and sidewalls 2

Figures 4-22 to 4-24 summarise and provide the proportions of stope surfaces influencing LHS performance.

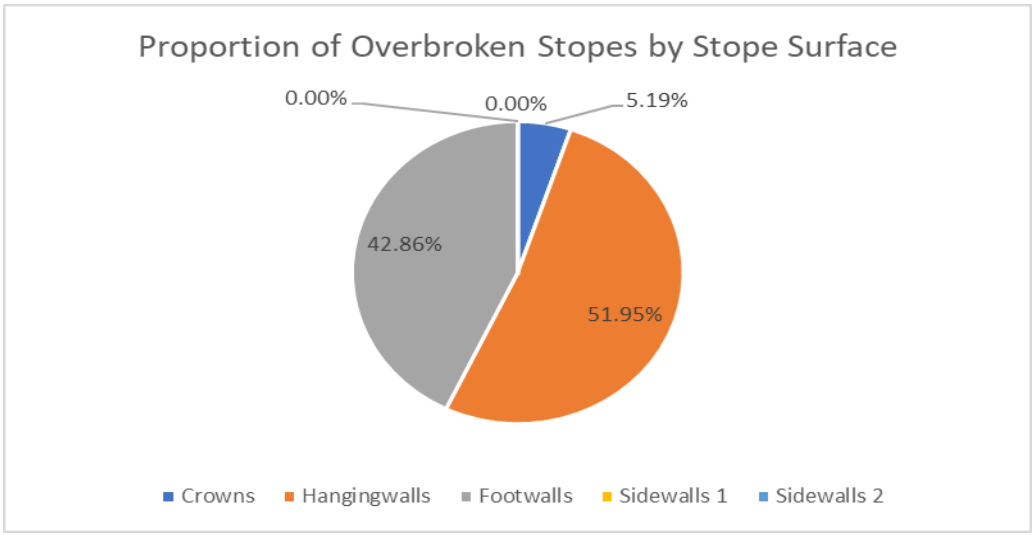


Figure 4-22: Proportion of over-broken stopes by stope surface

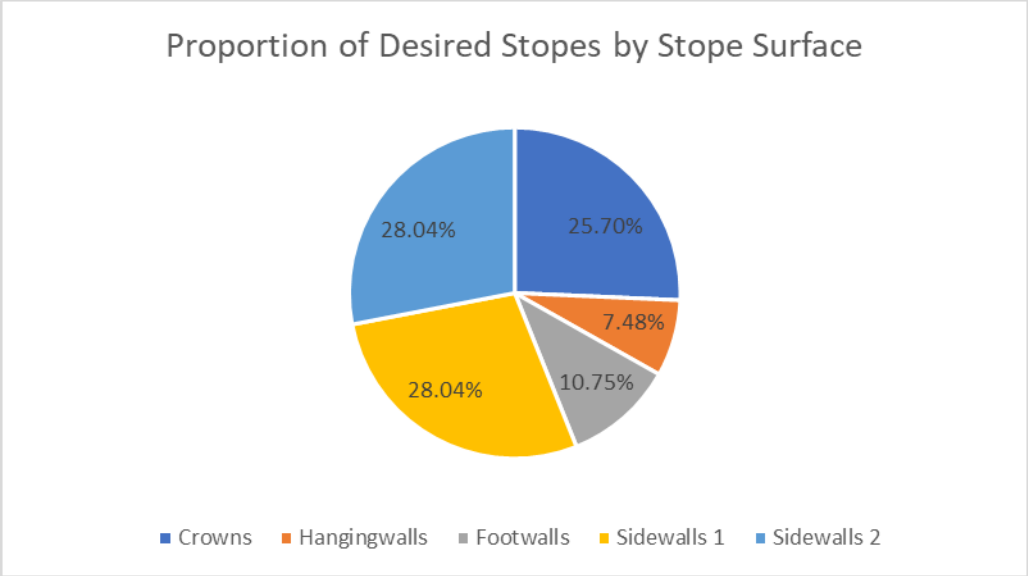


Figure 4-23: Proportion of desired stopes by stope surface

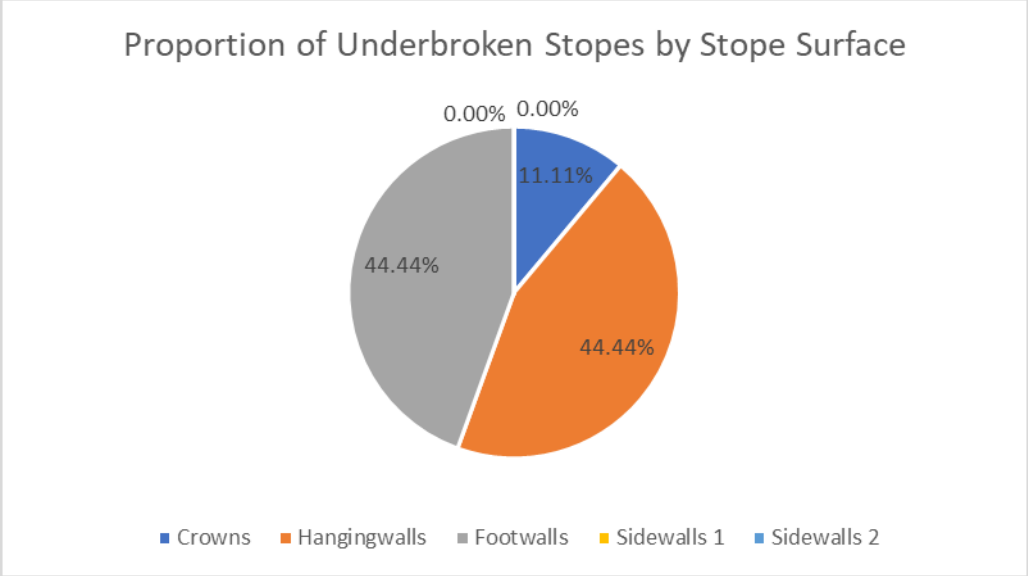


Figure 4-24: Proportion of under-broken stopes by stope surface

According to the reconciliation, 52% of the over-break occurs on hanging walls, while 42% occurs on footwalls, both owing to the presence of multiple faults and joints cutting across the surfaces. The remainder occurs on stope crowns and there is no undesired fragmentation on Sidewalls 1 and Sidewalls 2 because they connect with the open stope access drives (SADs). For the few stopes that had under-break as shown in Table 4-2, it was found that it occurred predominantly on

the hanging walls and footwalls where poor drilling execution prevents the development of full chargeable holes. There was little to no under-break on crowns and Sidewalls 1 and Sidewalls 2. The results indicate that the worst performances are on hanging walls and footwalls due to poor blast execution and wrong excavation geometry as will be shown in the next sections with drilling and blasting as well as excavation design.

4.2.2 LHS performance and drilling and blasting practices

Drilling and blasting practices at the mine were observed during the research period. This was to provide deeper insight as to how they influence the performance of LHS considering the scarcity of drill and blast data for the reconciled stopes. The scarce existing data and underground observations were however sufficient to understand how drilling and blasting practices at the mine affect LHS performance.

A. Drilling

To understand the drilling practices at the mine, the study analysed available drilling plans, returns and supervision sheets from mined-out stopes as well as stope health reports from 2022. Figure 4-25 shows a summary of drilling performance for the year 2022, highlighting the average compliance and drilled/undrilled stopes.

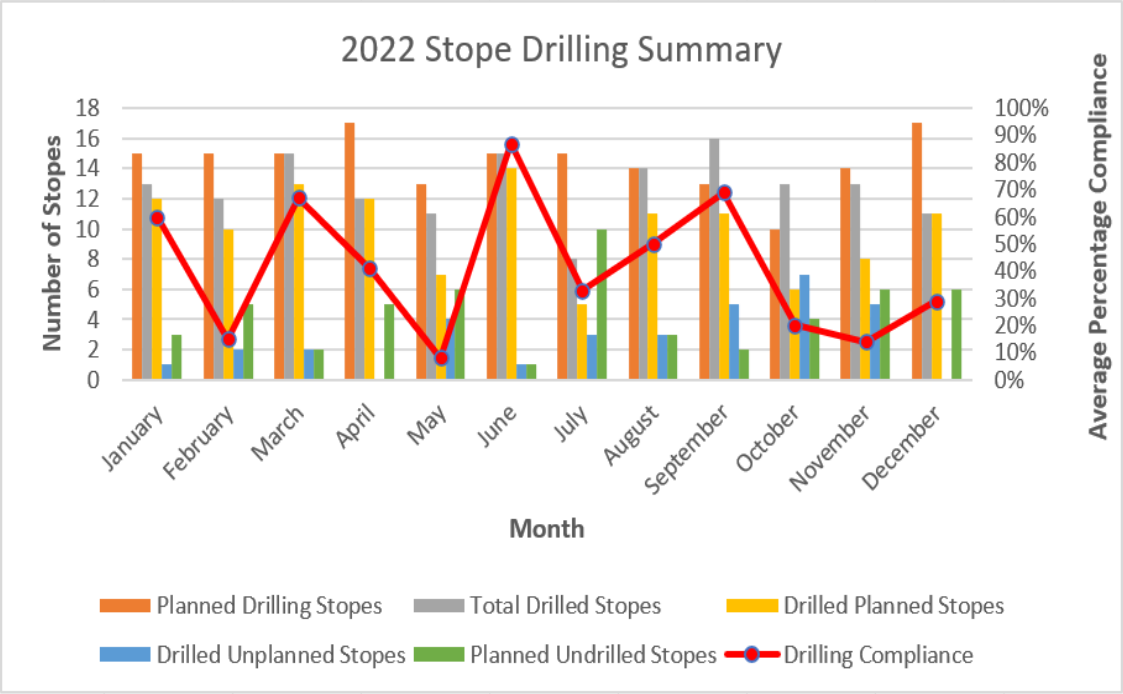


Figure 4-25: 2022 stope drilling summary

Over 30% of the planned stopes were not drilled and of the drilled stops, over 20% of them were not planned. The average drilling compliance for the year was a low 41%. Table 4-3 highlights some stopes and the general drilling issues contributing to their under-performance.

Table 4-3: Drilling and LHS performance

Stope Name	**Drilling Issues**	**Over-break/ Under-break**
100 4W CUT4 LHS 10E	Blocked holes on collars Holes in the ring holing into voids & backfill Footwall holes shortened	57.49%
100 3W CUT1 LHQ 04W	Blocked holes Machine breakdown Wrong percussion and feed pressure	-14.15%
100 4W CUT1 LHQ 01E	Missed holes Blocked holes	35.72%
100 4W CUT3 LHQ 05W	Blocked holes on collars Undrilled holes	38.11%
100 1BW CUT3 LHS 1A	Unmarked rings	49.62%
95 2W MPR04 LHS 01N	Holes in the ring holing into a void	28.42%
90 3W CUT2 LHP 11E	Blocked holes Holes in the ring holing into the backfill	71.73%
100 1BW CUT3 LHS03B	Holes drilled in the wrong location Different damping angle	41.73%
100 4W CUT1 LHQ 01E	Incomplete hole lengths Abandoned holes	35.72%
100 2AW CUT3 LHS 01E	Undrilled rings due to invisible laser lines Boom against backfill bags	22.98%

Blocked holes resulting from failure to use poly pipes when collaring, lack of hole inspection, and drilling into friable ground have a major contribution to poor LHS performance. Apart from the desktop study approach to understand past practices, underground visits also provided the following results, supplemented by Figures 4-26 to 4-30.



Figure 4-26: Water-logged drilling face, no pumping occurring



SOUTH DEEP No: A137717

FULL COMPLIANCE INTERNAL SECTION 54 — STOP — FIX VERIFY CONTINUE WORK

This full compliance notice is issued in the interest of Safety or Health

Date Issued: 27/09/2022 Time: 11:50

Issued to: LYDIA Ind No: Z-1455TD

Issued by: S. NJILO Ind No: Z7409165

Area of concern:

Support ☐ Flammable gas & ventilation ☑ Barring ☐

A Hazard ☐ Transport & Tramming ☐

Equipment ☐ Machinery ☐ Other (specify) ☐

Area / Location Stopped: East mine 100-1bw cut 4

Reason / Hazard: High temperature 35.0/39.0 C highest poor installation of vent columns damage seal precipitation of air

Signed as received by immediate Supervisor: DRAKE

Signed by relevant HOD:

Signed as completed by Immediate Supervisor:

Signed by relevant HOD:

Figure 4-27: Stop and fix order for hot working environment



Figure 4-28: Broken drill bit shanks

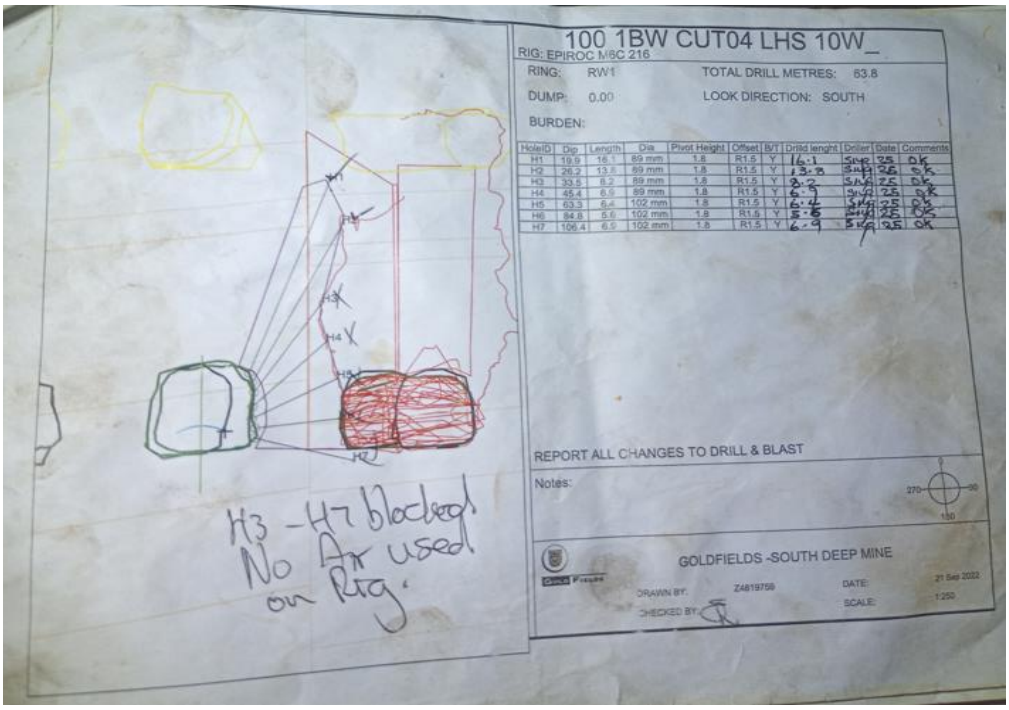


Figure 4-29: Blocked holes on drilling ring

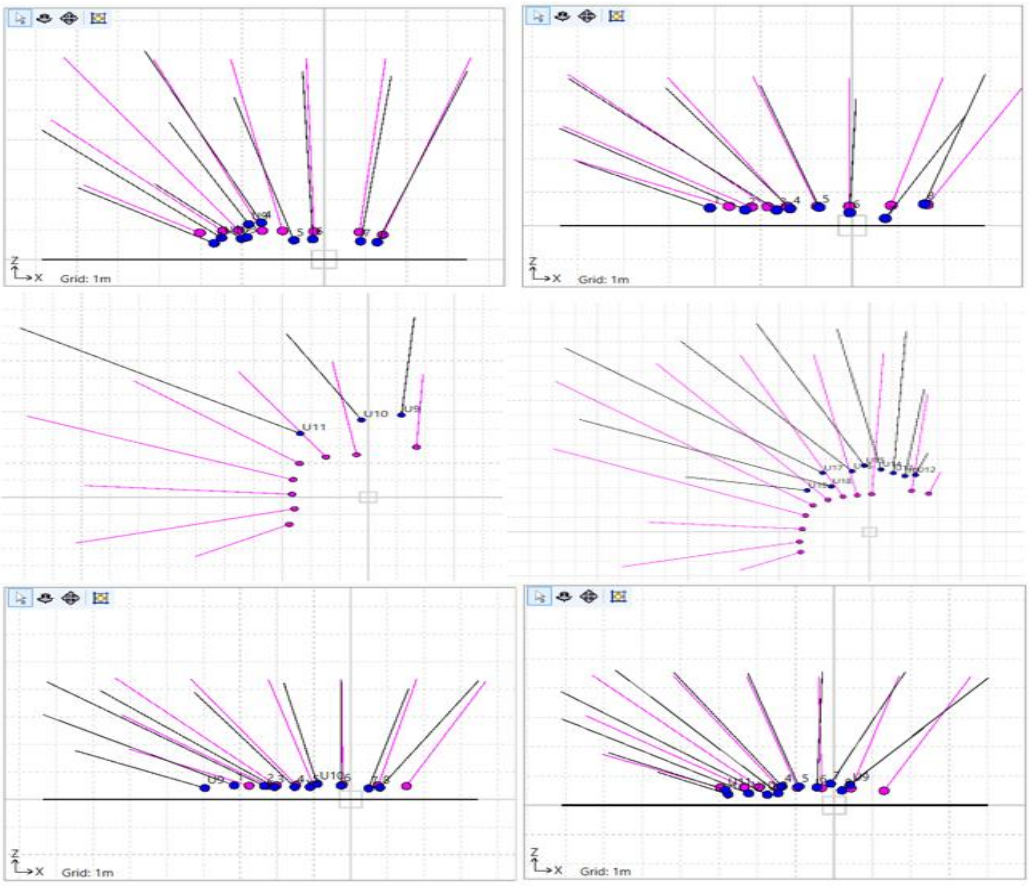


Figure 4-30: Drilling setup report. Planned (purple) and drilled (black) holes

- There were no laser lines drawn on some stopes causing challenges with positioning drill rigs;
- Some holes were marked too close to the walls creating a challenge for the positioning of the S7D drill rig as the carousel would bump on the hanging wall making it difficult to drill some rings;
- There was no use of guide tubes on the S7D rig when collaring to stabilize the drill steel and prevent hole deflection. In some instances, the stabilising stingers were not extended during drilling;
- Drill bit shanks were broken/damaged owing to wrong percussion and feed pressures (Figure 4-28);
- Water pressure for the rigs would be low and inconsistent, an indication of a mechanical problem at the source or feed pipes;
- The Angle Reading Instrument (ARI) unit was down, which led to the estimation of drilling angles, hole lengths, and drilling planes by operators based on their “experience”;
- Operators would chase the drilling target and pay less attention to opening the holes or re-drilling closed holes;
- Uncleared stopes increase the drill rig rigging time thereby delaying drilling and the completion of tasks;
- The working conditions around the drill rigs were not favorable as some areas were extremely hot and water logged (Figure 4-26 and Figure 4-27);
- Breakdowns and longer service periods increased the drilling turnaround time, delaying stope completion;
- There was inconsistent use of poly pipes and no air drilling (for hole flushing) on fractured ground leading to the blockage of drilled holes (Figure 4-29) and

in some instances, stuck drilling rods in the holes. Not only does this increase operating costs, but it also slows down the drilling process;

- An increase in the burden and spacing for some stopes created boulders that would fall off and create back breaks on the stope brows;
- While some holes show that they have been drilled on the same plane, their angles are different from the plan as shown in Figure 4-30 from the M6C drill rig report. This meant collars would be close together while toe spacing was widened, creating the risk of poor fragmentation when blasting; and
- The automated M6C drill rig offered a better operational experience than the S7D drill rig. The automatic tracking of drilling metrics also makes it more efficient for quality evaluation purposes.

B. Blasting

Charging and subsequent blasting follow drilling. The quality of the blast is determined largely by drilling activities. Charging returns, reports and underground observations were sufficient to identify the key issues affecting blasting and subsequently LHS performance. Of note were the following:

- The Automated BME charging truck is more efficient than the manual K2 charging machine although it is slower since it is in its trial phase. In addition to the benefit of quick and more accurate charging, it also presents a lower work load on operators when charging up holes. Delays in changing from one hole to the next in manual charging led to the emulsion reacting and hardening inside the charging lance;
- The spider stem plug used for plugging holes did not match the diameter of the holes and the emulsion would flow out. More emulsion would fall out when the tippet is not used in placing the second detonator for coupled charges;

- In one of the charging machines there was a fault where emulsion was found in the water tank and the flushing tank was full of emulsion causing blockages in the charging lance;
- Holes charged with emulsion of a high density would have the weight of the explosive exerted on the spider stemming plug and it would fall off in instances where the period between charging and blasting was extended. In other instances, the emulsion would shear, reducing its reliability in fragmenting rock;
- Some emulsion was lost to fissures and holes intersecting each other while short drilled holes would be overcharged threatening the integrity of the stope brow and promoting over-break;
- Holes on friable ground as well as crushed and blocked holes were not charged and potentially caused under-breaking and boulders. Explosive energy into the friable ground would cause unplanned movement of ground. The cracked holes also present the risk of detonating other holes prematurely or freezing them as gases escape to unplanned areas;
- Within some rings, holes were left uncharged and untimed, increasing the likelihood of under-break;
- On one charge return, reamer holes were indicated to have been charged when in practice they should not be charged;
- The design hole length did not align with the actual charging length because of holing into voids;
- The batch counter was not working on one of the charge masters;
- A stope took up to 2 weeks between charging and blasting with excessive fallout and slumping of the emulsion from the holes observed; and

- The AECL emulsion was generally preferred by charging teams over the BME emulsion product based on ease of use. However, a separate study into the performance of each of the explosive products could provide useful insights for improving blasting and subsequently LHS performance.

4.2.3 LHS performance and design considerations

A. Stope mining sequence

Figures 4-31 to 4-33 show the performance of Long-hole stopes based on the stope mining sequence. The same rationale from Equation 4.1 applies to determine the performance of the primary, secondary, and sequential stopes.

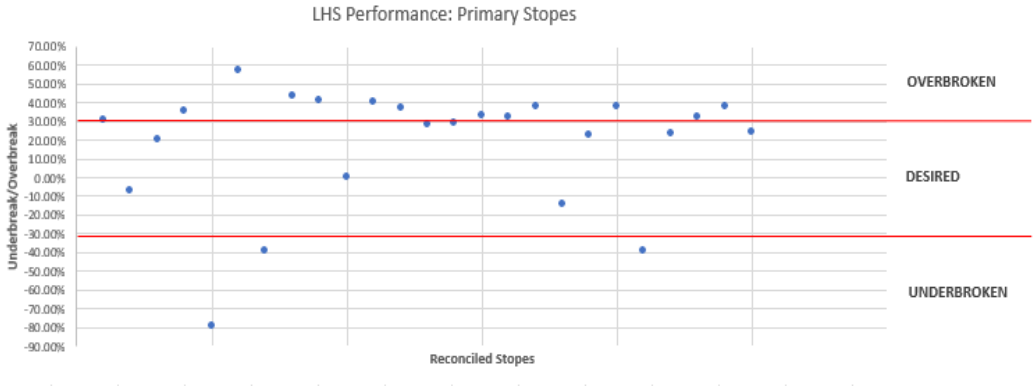


Figure 4-31: LHS performance and primary stopes

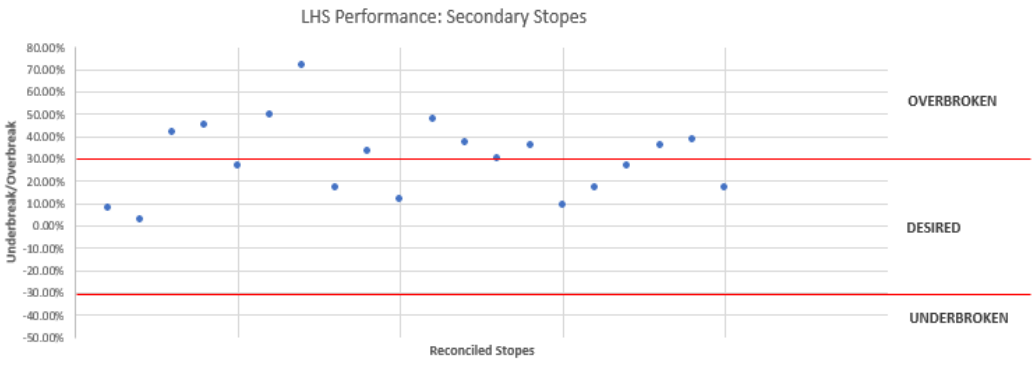


Figure 4-32: LHS performance and secondary stopes

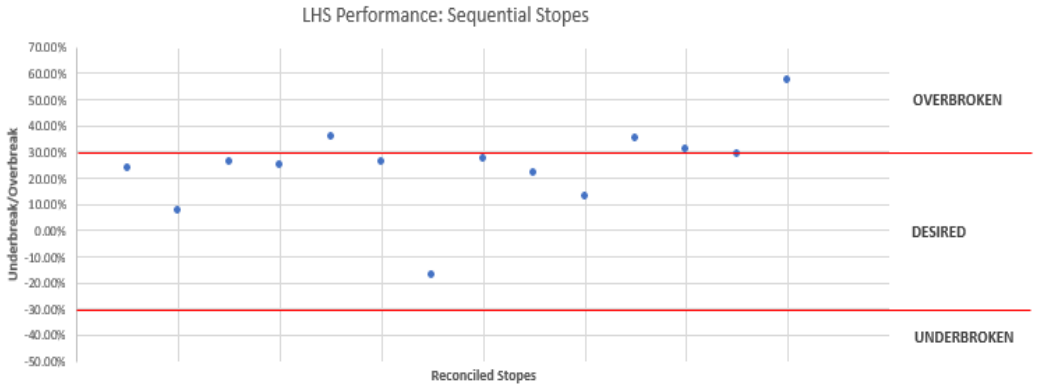


Figure 4-33: LHS performance and sequential stopes

Primary and secondary stopes each show more than 50% over-break with insignificant to no under-break respectively. The trend is different for sequential stopes that indicate more compliant and stable performance shown by over 70% of the stopes falling in the desired range. Figures 4-34 to 4-39 further indicate the proportions and severities of LHS performance based on the mining sequence.

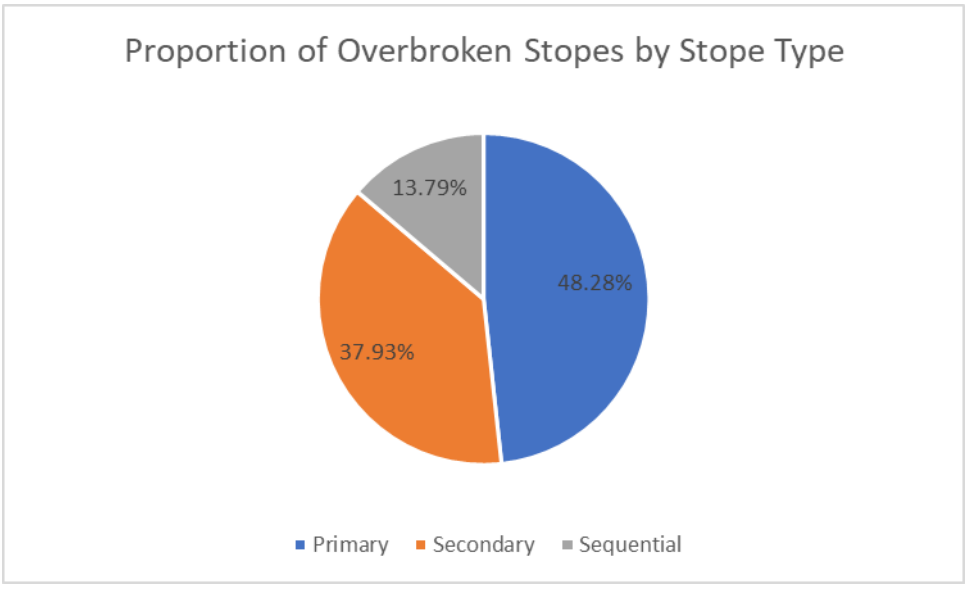


Figure 4-34: Proportion of over-broken stopes by mining sequence

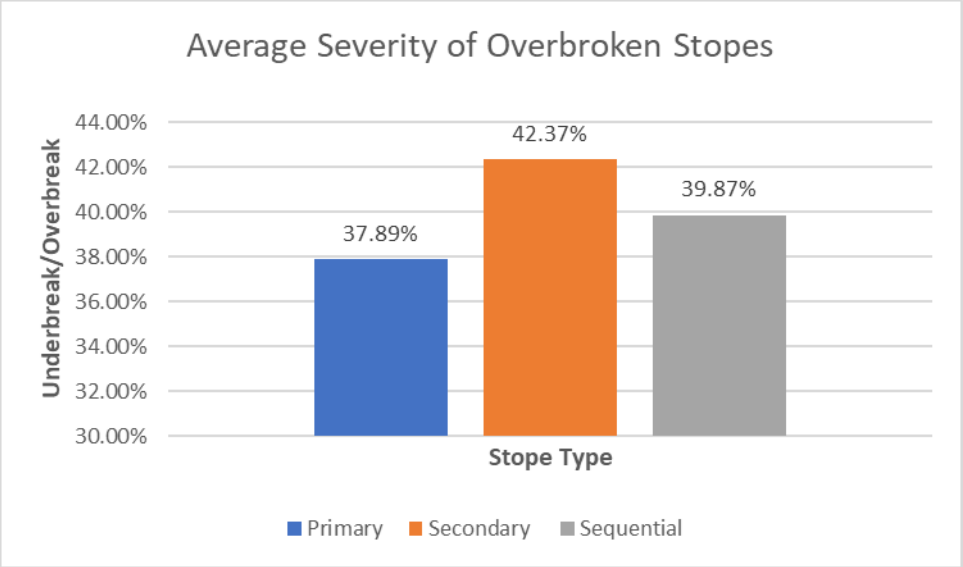


Figure 4-35: Severity of over-broken stopes by mining sequence

Primary and secondary stopes contribute to over 86% of the over-broken stopes. While primary stopes make up the majority of the over-broken stopes, it is critical to note that subsequent secondary and sequential stopes are more severely damaged than the primary stopes. The excess material could be a result of poor backfilling adjacent to the secondary stopes, causing some backfill material to fall into the stope.

In ranking the contributions of mining sequences to poor LHS performance, primary stopes prove to be the worst performers, closely followed by secondary stopes and sequential stopes are the least problematic. However, given that the results are based on historic data and more secondary and sequential stopes are yet to be mined, there could be a different trend as mining progresses.

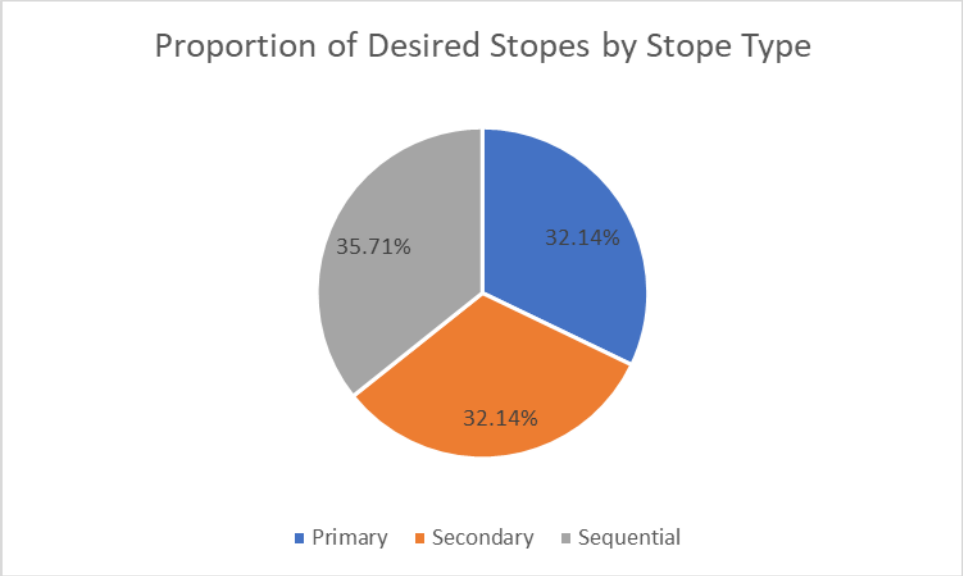


Figure 4-36: Proportion of desired stopes by mining sequence

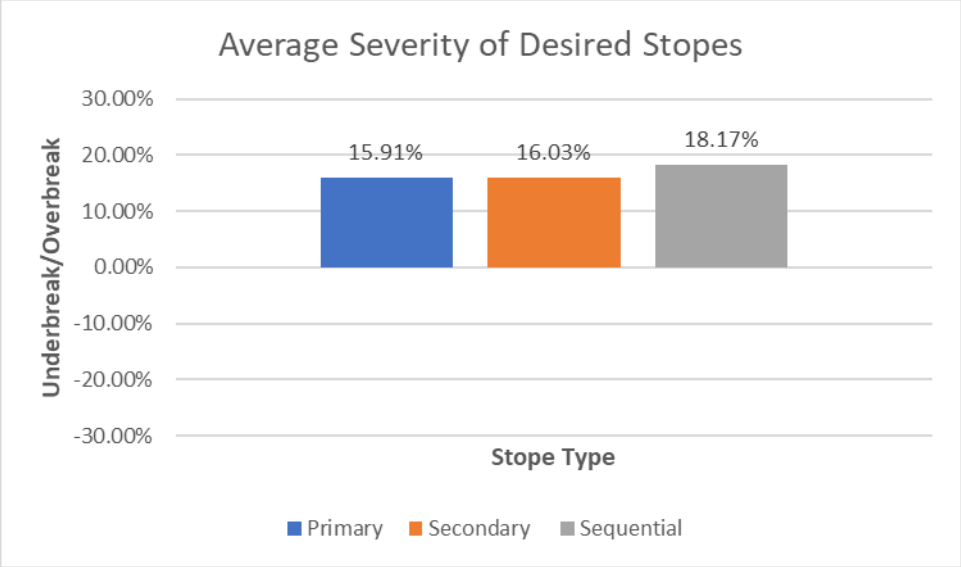


Figure 4-37: Severity of desired stopes by mining sequence

There is a balance in the proportion of desired stope performances with each mining sequence contributing an almost equal amount. The severities are directly proportional to the proportions and are almost equal as well. These trends are of little significance to this study.

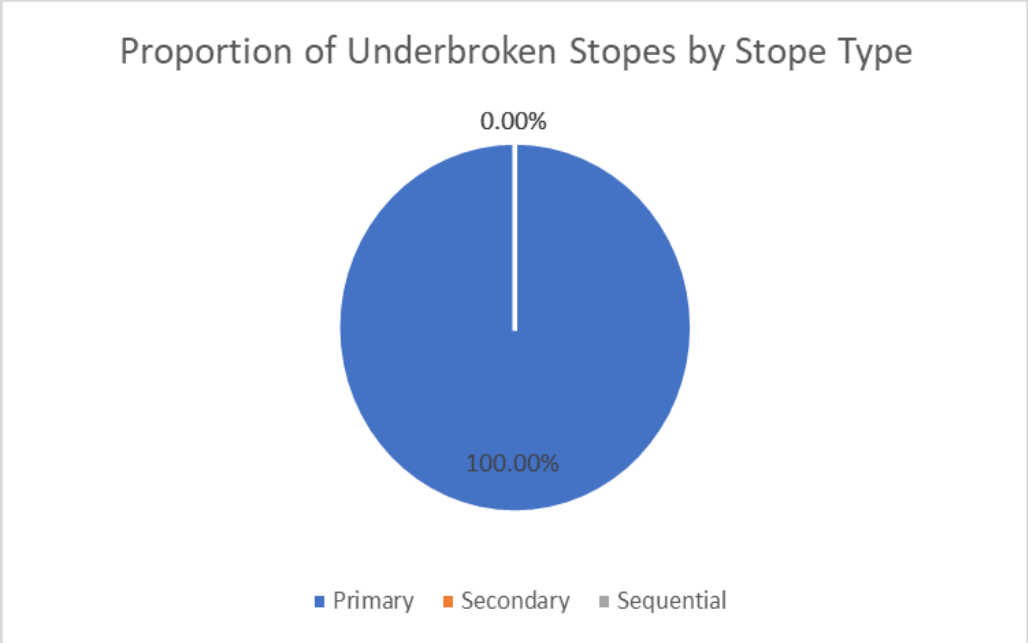


Figure 4-38: Proportion of under-broken stopes by mining sequence

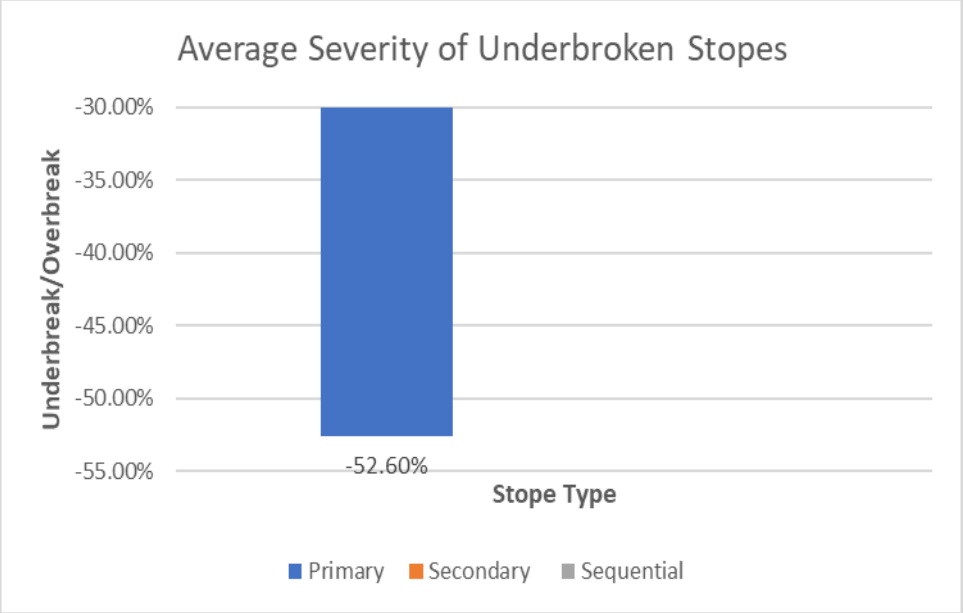


Figure 4-39: Severity of under-broken stopes by mining sequence

All under-broken stopes were primary stopes with a very high severity. The general trend of the results has shown that there is little to be drawn from under-broken stopes due to their low number. An increase in under-broken stopes would introduce new insights into LHS performance.

B. Excavation dimensions

The impact of stope surface dimensions was analysed to develop an understanding of how design considerations affected LHS performance. The relationship is worth exploring because some of the over-broken stope surfaces show that excavation dimensions yielded high hydraulic radius (HR) values. An evaluation of the critical mining span based on the hydraulic radius concept conducted by SRK Consulting recommended mining spans yielding HR values of 6.0 (Joughin et al., 2006). This value has been adopted as a standard for HR performance at the mine, with values below 6 considered desirable while those above 6 are undesirable because they are susceptible to instability and failure. Figures 4-40 to 4-44 show HR vs Stope Surface Performance plots.

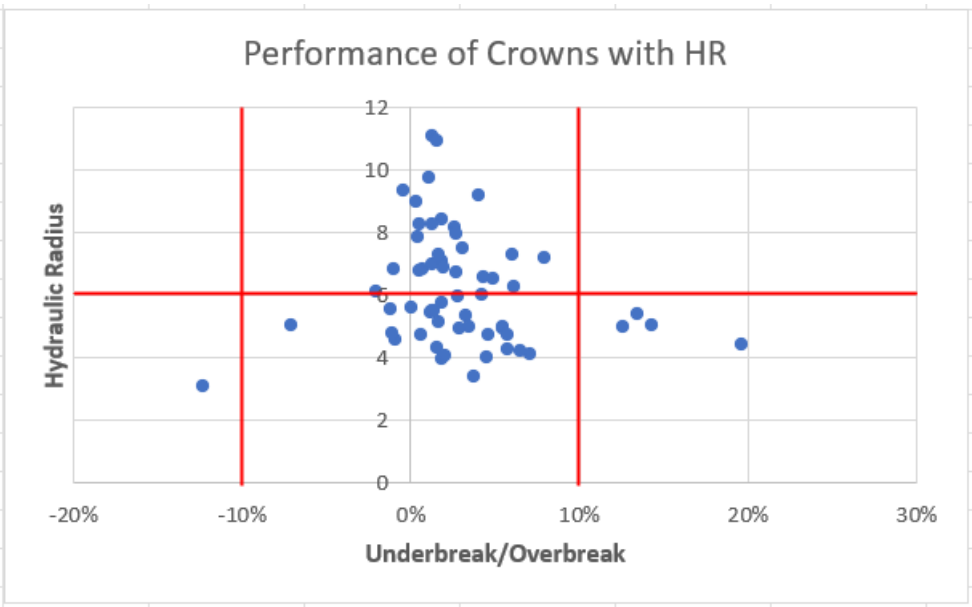


Figure 4-40: Performance of crowns with HR

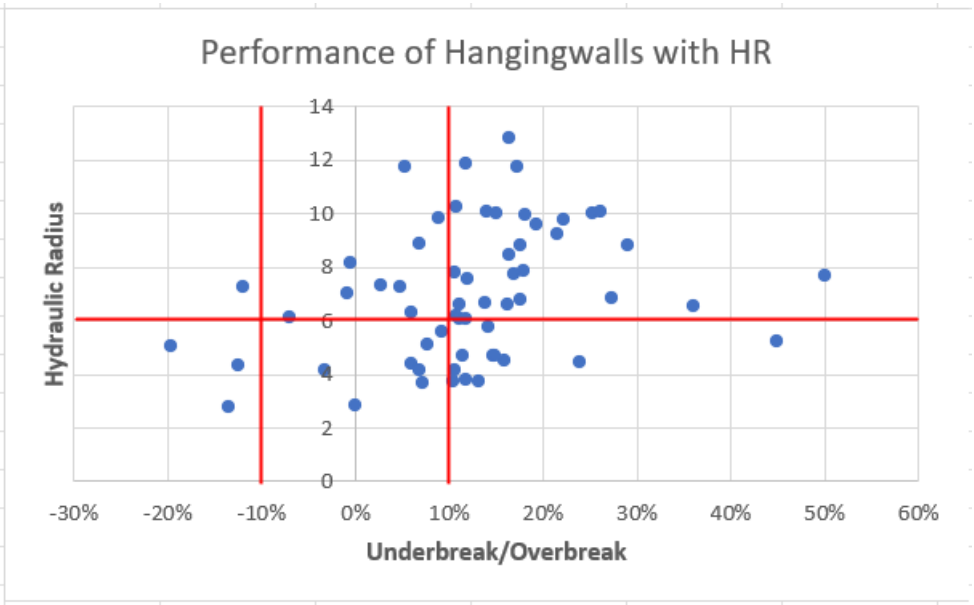


Figure 4-41: Performance of hanging walls with HR

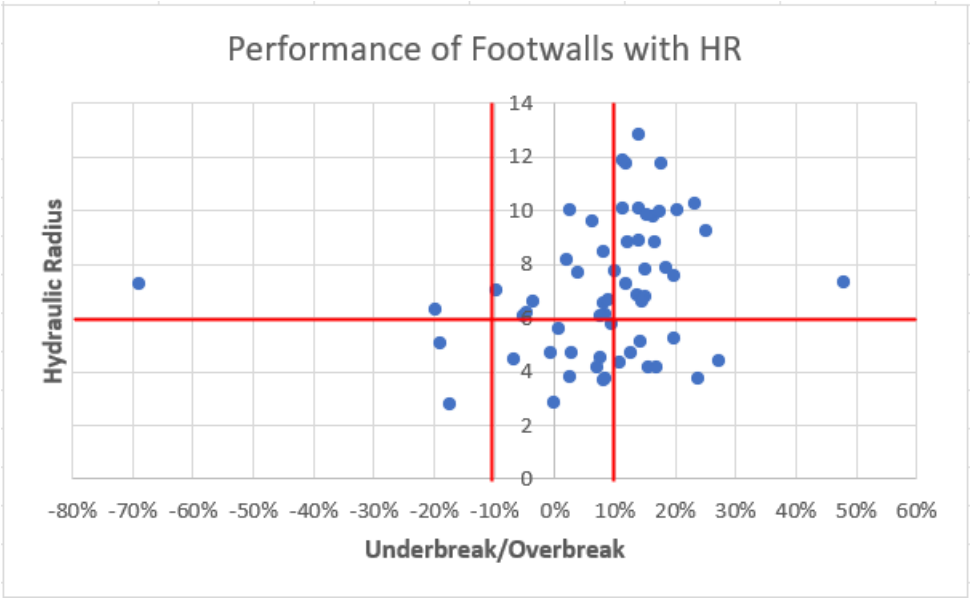


Figure 4-42: Performance of footwalls with HR

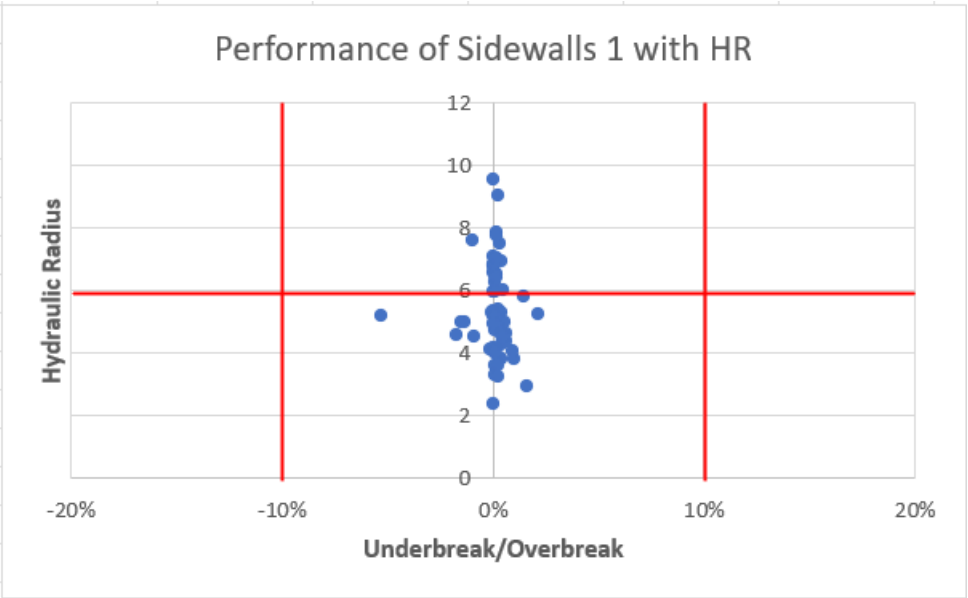


Figure 4-43: Performance of sidewalls 1 with HR

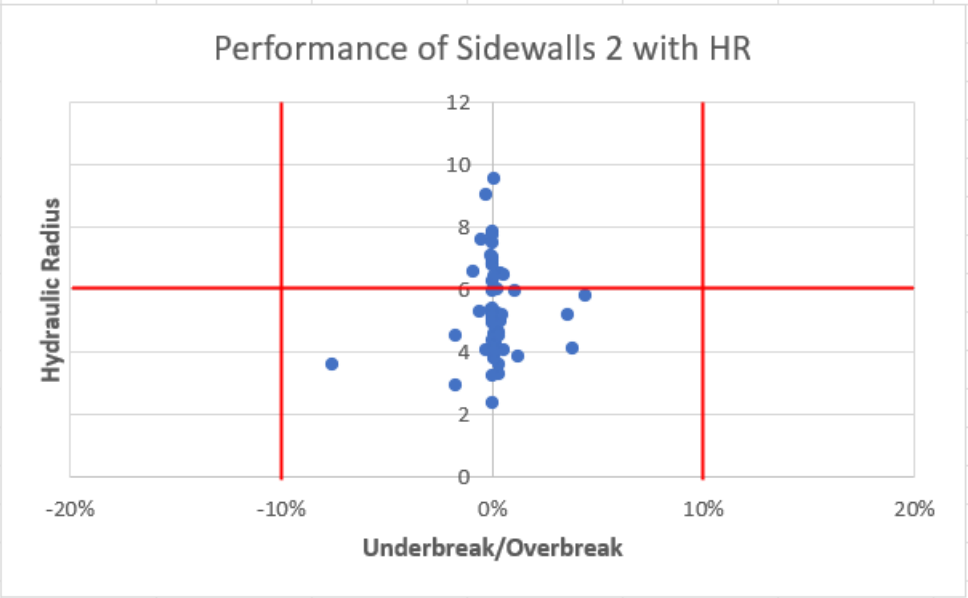


Figure 4-44: Performance of sidewalls 2 with HR

As shown in Chapter 4.2.1.C, the undesired over-break and under-break occurred prevalently on hanging walls and footwalls. Notably, of the undesired fragmentation on the hanging walls and footwalls, over 74% on each of the stope surfaces had an HR above 6. This is a strong indication that large excavation spans contribute to instability and subsequently over-break on these surfaces. There is insignificant

to no evidence linking excessive over-break and under-break to HR on crowns, sidewalls 1, and sidewalls 2.

In assessing the data suitability to model HR versus over-break/under-break and predict LHS performance based on HR, it was noticed that the data coverage and composition would not allow for the fitting of a linear model as shown in the scatter plots (Figure 4-40 to Figure 4-44). The behaviour of the relationship between LHS surface performance and HR can however be predicted by the application of a multi-variate model. Based on the reconciled stopes, the model can be used for the prediction of over-break/under-break on crowns, hanging walls, footwalls, sidewalls 1, and sidewalls 2 using excavation dimensions. Table 4-4 summarises the multi-variate model in Appendix F.

Table 4-4: Multi-variate model summary

Parameter	Crown HR	Hanging wall HR	Footwall HR	Sidewall 1 HR	Sidewall 2 HR
Constant	-0.15	-0.56	-0.64	0.54	0.46
Length (m)	4.09	7.03	6.80	-0.49	-0.46
Width (m)	8.41	0.75	1.09	4.71	4.71
Height (m)	0.18	8.00	8.20	4.87	4.96
Crown O/B (%)	-0.19				
Crown U/B (%)	0.26				
Hanging wall O/B (%)		1.08			
Hanging wall U/B (%)		-0.18			
Footwall O/B (%)			0.56		
Footwall U/B (%)			0.54		
Sidewall 1 O/B (%)				-0.11	
Sidewall 1 U/B (%)				0.30	
Sidewall 2 O/B (%)					0.10
Sidewall 2 U/B (%)					0.46
CoD or R-squared	0.98	0.88	0.87	0.79	0.79
MedAE	0.17	0.61	0.60	0.30	0.28
MAPE	0.03	0.11	0.11	0.08	0.08

Equation 4.3 simplifies the model into a mathematical function:

$$y = m_1x_1 + m_2x_2 + m_3x_3 + m_4x_4 + c \qquad (4.3)$$

Where y is the HR, $m_{1,2,3,4}$ represent the independent variables, $x_{1,2,3,4}$ are the corresponding model coefficients and c is the constant or intercept. In this case, m_1x_1, m_2x_2, m_3x_3 and m_4x_4 are the slopes or coefficients concerning the independent feature. It indicates that if we increase the value of x_1 by one unit then m_1 shows by how much value it will affect the HR index, and this is similar concerning m_2x_2, m_3x_3 and m_4x_4. Making x_4 the subject of the formula gives an estimate of the expected over-break on each stope surface. The high co-efficient of determination values (0.98, 0.88, 0.87, 0.79, and 0.79) support the suitability of the model in predicting over-break and under-break.

C. General

An observation was made about design considerations where it was noted that in some instances, the distances to the face marked on the drilling plan would not correspond with the actual distances underground. This was indicative of a gap between the dates of tunnel scanning, actual design dates, and drilling dates. The profile of the face was slightly changed owing to movement, possible deformation, and/or fall of ground and no subsequent re-scanning. It would then create problems with drilling machine positioning within the stope, something that affects the drilling quality as already discussed.

4.2.4 LHS performance and combined factors

To further understand the intersectionality of the factors influencing LHS performance at South Deep Gold Mine, the study analysed how the combination of mining environments, reef horizons, and stope mining sequence influenced performance. Over-broken stopes provided sufficient data points for this evaluation approach while the under-broken stopes were not considered as they did not provide sufficient data points for logical deductions. Each of the three factors in the analysis was assigned weights based on their over-break proportions (frequency) and extent of over-break (severity) as shown in Tables 4-5 to 4-7. These weights were used to create a matrix that informs how the mine may manage over-break.

Table 4-5: Stope type weighting by over-break proportion and severity

Stope Type	Proportion of Over-broken Stopes (Frequency)	Average Over-break Percentage (Severity)	Weight
Primary	48.28%	37.89%	18.29%
Secondary	37.93%	42.37%	16.07%
Sequential	13.79%	39.87%	5.50%

Table 4-6: Mining environment weighting by over-break proportion and severity

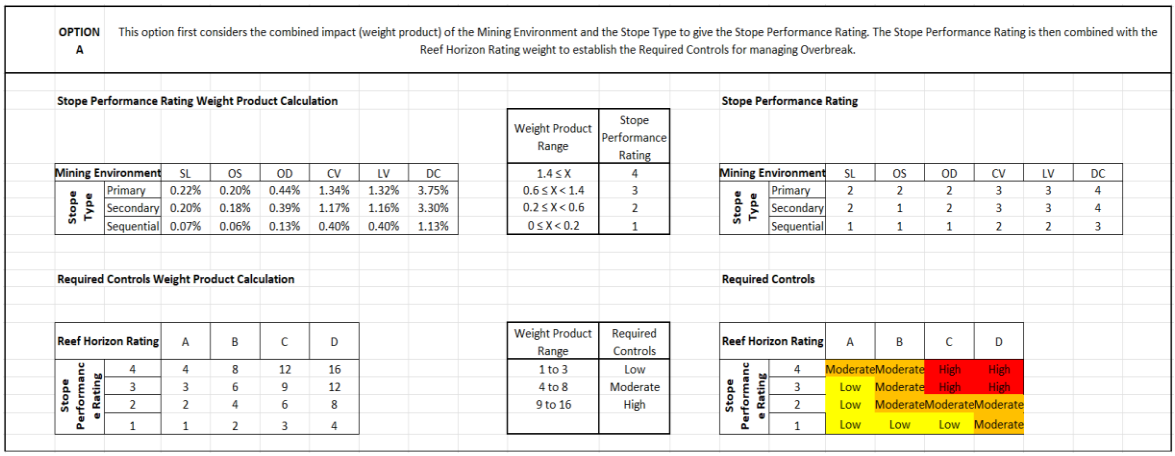
Mining Environment	Proportion of Over-broken Stopes (Frequency)	Average Over-break Percentage (Severity)	Weight
De-stress Cut	51.72%	39.65%	20.51%
Lava	20.69%	34.88%	7.22%
Conventional	13.79%	52.97%	7.30%
Open Development	6.90%	34.88%	2.41%
Open Stope	3.45%	32.06%	1.11%
Solid	3.45%	35.21%	1.21%

Table 4-7: Reef horizon weighting by over-break proportion and severity

Reef Horizon in Stratigraphy Sequence	Proportion of Over-broken Stopes (Frequency)	Average Over-break Percentage (Severity)	Weight	Reef Horizon Range	Reef Horizon Rating	Weight
VCR	8.44%	36.97%	3.12%	9.15 ≤ X	D	4
MBT	24.10%	37.98%	9.15%	3.02≤ X < 9.15	C	3
MBB	9.64%	37.19%	3.59%	1.74≤ X < 3.02	B	2
MIQ	4.82%	34.72%	1.67%	0 ≤ X < 1.74	A	1
MIT	7.23%	37.25%	2.69%			
MIB	7.23%	34.92%	2.52%			
MAD	6.02%	37.55%	2.26%			
MAC	9.64%	44.29%	4.27%			
ED	9.64%	42.38%	4.09%			
ECT	0.00%	0.00%	0.00%			
ECMQ	0.00%	0.00%	0.00%			
ECMC	6.02%	47.26%	2.85%			
ECBQ	0.00%	0.00%	0.00%			
ECB	3.61%	43.27%	1.56%			
ECBAQ	0.00%	0.00%	0.00%			
ECBA	3.61%	56.30%	2.03%			

It is important to note that unlike the stope type and mining environment, the occurrence of individual reef horizons within a stope is not mutually exclusive. Several reef horizons may influence the performance of a single stope and in assigning weights, the sum of each of the products of surface proportions and severities is used to determine the range within which they will fall. Letters A, B, C, and D were used to represent the reef horizon ratings within the weighted ranges.

To accommodate all the factors, two two-dimensional matrices were favoured over a three-dimensional matrix due to complexities in formulating the latter. Figure 4-45 and Figure 4-46 illustrate the working logic, calculations (left), and conversions (centre) used to derive the two matrices (right).



OPTION A This option first considers the combined impact (weight product) of the Mining Environment and the Stope Type to give the Stope Performance Rating. The Stope Performance Rating is then combined with the Reef Horizon Rating weight to establish the Required Controls for managing Overbreak.

Stope Performance Rating Weight Product Calculation

Mining Environment		SL	OS	OD	CV	LV	DC
Stope Type	Primary	0.22%	0.20%	0.44%	1.34%	1.32%	3.75%
	Secondary	0.20%	0.18%	0.39%	1.17%	1.16%	3.30%
	Sequential	0.07%	0.06%	0.13%	0.40%	0.40%	1.13%

Weight Product Range	Stope Performance Rating
1.4 ≤ X	4
0.6 ≤ X < 1.4	3
0.2 ≤ X < 0.6	2
0 ≤ X < 0.2	1

Stope Performance Rating

Mining Environment		SL	OS	OD	CV	LV	DC
Stope Type	Primary	2	2	2	3	3	4
	Secondary	2	1	2	3	3	4
	Sequential	1	1	1	2	2	3

Required Controls Weight Product Calculation

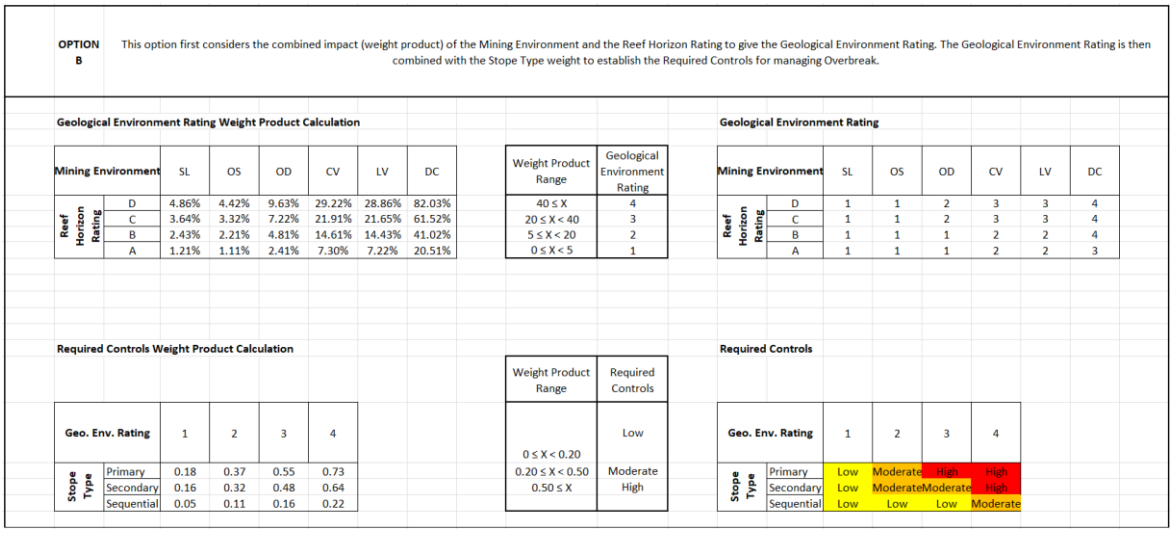
Reef Horizon Rating		A	B	C	D
Stope Performance Rating	4	4	8	12	16
	3	3	6	9	12
	2	2	4	6	8
	1	1	2	3	4

Weight Product Range	Required Controls
1 to 3	Low
4 to 8	Moderate
9 to 16	High

Required Controls

Reef Horizon Rating		A	B	C	D
Stope Performance Rating	4	Moderate	Moderate	High	High
	3	Low	Moderate	High	High
	2	Low	Moderate	Moderate	Moderate
	1	Low	Low	Low	Moderate

Figure 4-45: Over-break control matrix (Option A)



OPTION B This option first considers the combined impact (weight product) of the Mining Environment and the Reef Horizon Rating to give the Geological Environment Rating. The Geological Environment Rating is then combined with the Stope Type weight to establish the Required Controls for managing Overbreak.

Geological Environment Rating Weight Product Calculation

Mining Environment		SL	OS	OD	CV	LV	DC
Reef Horizon Rating	D	4.86%	4.42%	9.63%	29.22%	28.86%	82.03%
	C	3.64%	3.32%	7.22%	21.91%	21.65%	61.52%
	B	2.43%	2.21%	4.81%	14.61%	14.43%	41.02%
	A	1.21%	1.11%	2.41%	7.30%	7.22%	20.51%

Weight Product Range	Geological Environment Rating
40 ≤ X	4
20 ≤ X < 40	3
5 ≤ X < 20	2
0 ≤ X < 5	1

Geological Environment Rating

Mining Environment		SL	OS	OD	CV	LV	DC
Reef Horizon Rating	D	1	1	2	3	3	4
	C	1	1	2	3	3	4
	B	1	1	1	2	2	4
	A	1	1	1	2	2	3

Required Controls Weight Product Calculation

Geo. Env. Rating		1	2	3	4
Stope Type	Primary	0.18	0.37	0.55	0.73
	Secondary	0.16	0.32	0.48	0.64
	Sequential	0.05	0.11	0.16	0.22

Weight Product Range	Required Controls
0 ≤ X < 0.20	Low
0.20 ≤ X < 0.50	Moderate
0.50 ≤ X	High

Required Controls

Geo. Env. Rating		1	2	3	4
Stope Type	Primary	Low	Moderate	High	High
	Secondary	Low	Moderate	Moderate	High
	Sequential	Low	Low	Low	Moderate

Figure 4-46: Over-break control matrix (Option B)

[Option A] Two factors (mining environment and stope type) have their weights combined to give a product with a range between 0% and 4%. The values within this range are standardised to give a stope performance rating in the first matrix.

This product (stope performance rating) is then combined with the reef horizon rating to give a product range between 1 and 16.

[Option B] Two factors (mining environment and reef horizon) have their weights combined to give a product with a range between 0% and 100%. The values within this range are standardised to give a geological environment rating in the first matrix. This product (geological environment rating) is then combined with the stope type weighting to give a product range between 0 and 1.

The values in this range guide on the level of controls that would be required to manage over-break in the second matrix. Figure 4-47 shows a platform that returns values of the required over-break controls based on stope inputs.

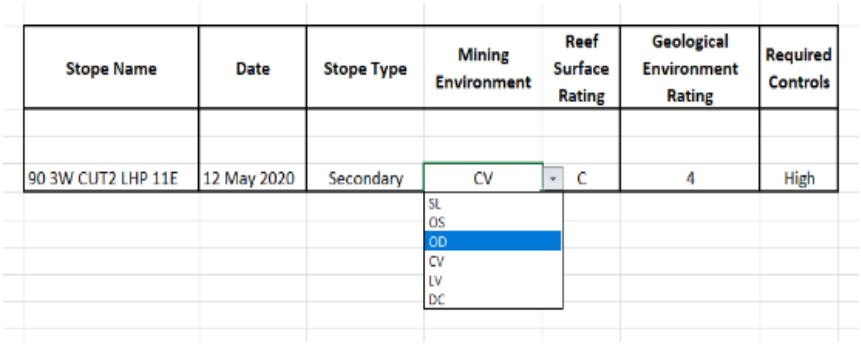


Figure 4-47: Required controls calculator

The calculator applies the IF function with INDEX and MATCH on MS Excel to return first the stope performance rating [Option A] or the geological environment rating [Option B]. From this, the required over-break controls will be determined based on given conditions of stope type (primary, secondary, or sequential), mining environment (SL, OS, OD, CV, LV, or DC) and reef horizon rating (A, B, C, or D). The required controls will not only be a useful tool in the prediction of over-break when coupled with the multi-variate model, but will further work in tandem with the

drill and blast recommendations indicated in Chapter 5 to improve LHS performance. The matrix is essential for controlling factors outside human control.

5 CONCLUSION AND RECOMMENDATIONS

This chapter synthesises the findings of the research and provides insights obtained from the research work. In the process, it answers the research questions and meets the objectives initially set while setting a hierarchy of key issues contributing to each factor. This will ensure the recommendations are feasible and actionable.

5.1 Conclusion

The study sought to investigate the performance of LHS at South Deep Gold Mine. Throughout the study, LHS performance was assessed in terms of over-break and under-break as they were the key problems at the mine affecting stope turnaround time. To solve the problem, the research considered the impact of the unique mining environments, drilling and blasting practices as well as design aspects on LHS performance.

This multi-faceted approach has brought an understanding of how and why LHS perform the way they do. It has further opened room for the improvement of LHS performance and the subsequent reduction of the stope turnaround time.

The findings from the research questions led to the emergence of two leading themes. The first theme corresponding to the influence of geological environments and design aspects relates to the application of engineering principles in the mining environment, within the jurisdiction of the mining engineer / mine planner. The second theme corresponding to drilling and blasting practices relates to operational excellence, within the jurisdiction of the miner. The success of LHS performance hinges on the interplay and balance of these two themes. Figure 5-1 summarises

the research findings while Figures 5-2 to 5-4 rank the individual issues relating to each of the research questions in order of their importance.

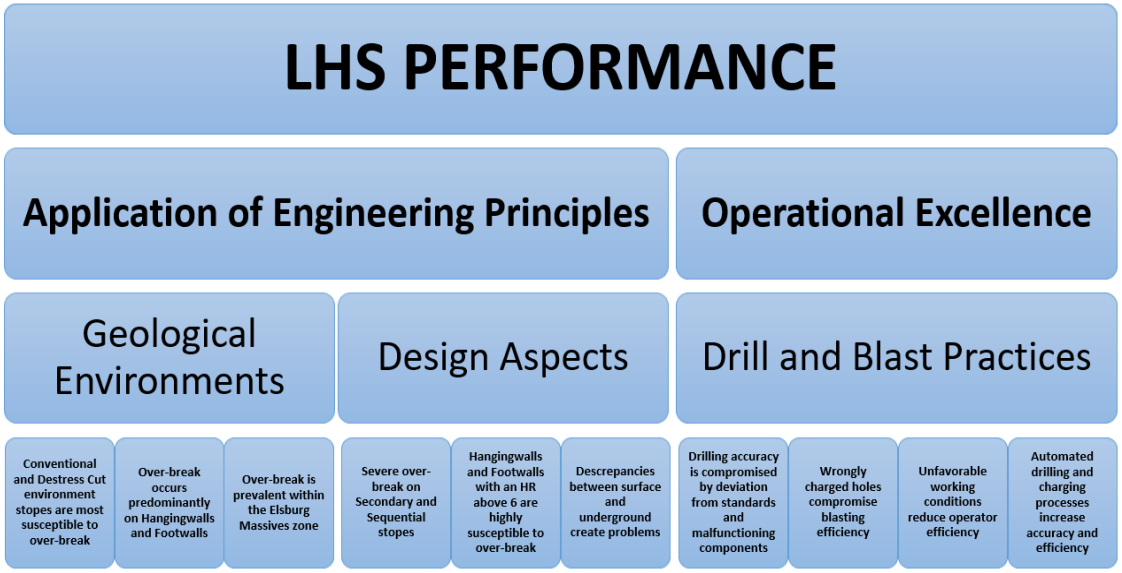


Figure 5-1: Summary of research findings

5.1.1 What is the influence of geological environments on LHS performance?

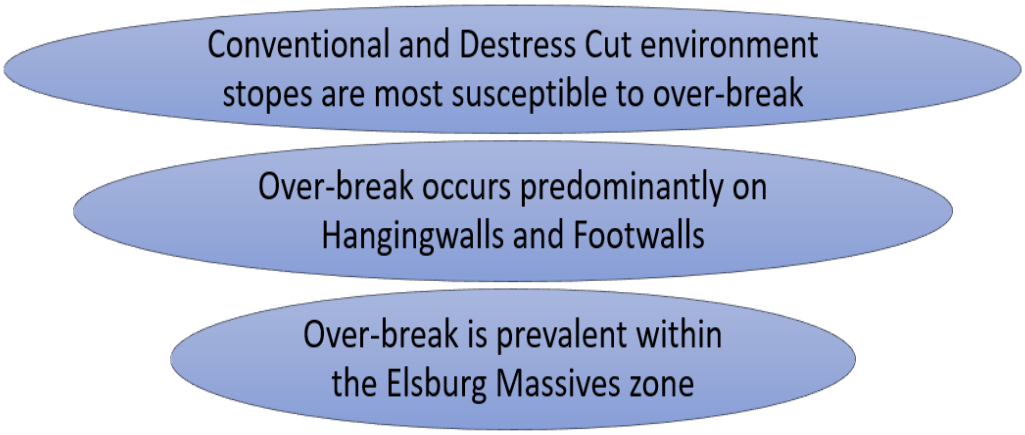


Figure 5-2: Influence of geological environments on LHS performance

i. Stopes occurring under de-stress cut environments and conventional stopes constitute the highest proportions and severities of over-break (O/B)

due to the release of remnant energy along de-stress cut boundaries while those under solid and open development environments are more stable and yield the desired fragmentation.

ii. The most severe damage and a high proportion of over-break occur on hanging walls and footwalls because most drilling and blasting deviations occur on these surfaces. Sidewalls and crowns mostly have the desired fragmentation.

iii. Above the foreknown impacts of geological complexities (dykes, faults, joints, etc.) on LHS performance, the presence of reef horizon contacts along stope boundaries was found to affect LHS performance too. Stopes intercepted by MBT, MAC, and ED reef horizons had a high combined proportion and severity of over-break because they comprise almost equal compositions of quartzite and conglomerate within the Elsburg Massives zone. The presence of both formations in equal proportions creates weaker and unstable bonds within the parent rock. On the other hand, ECT, ECMQ, ECBQ, and ECBAQ reef horizons found in the Elsburg Individuals zone did not influence over-break as they are characterised by well-defined conglomeratic units.

5.1.2 How do design aspects at South Deep Gold Mine affect LHS performance?

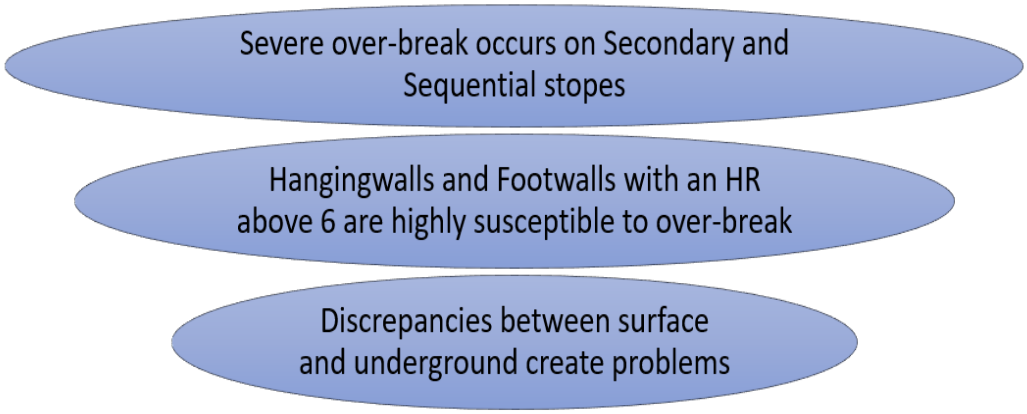


Figure 5-3: Influence of design aspects on LHS performance

i. Although the majority of over-break occurs on primary stopes, secondary and sequential stopes exhibit high over-break severities. The chosen stope mining sequence influences LHS performance because poor backfilling adjacent to secondary or sequential stope has the potential to increase over-break.

ii. Hanging walls and footwalls with HR values above 6 are susceptible to poor performance as shown by their over-break proportions over 74% each. HR is however a minor issue with sidewalls because they take up the shorter geometries of the stopes (height and width).

iii. Discrepancies between drilling plan dimensions and actual dimensions underground (UG) caused by longer periods between stope design and stope drilling without re-scanning to identify fallout, create challenges with drilling.

5.1.3 How do current drilling and blasting practices at South Deep Gold Mine affect LHS performance?

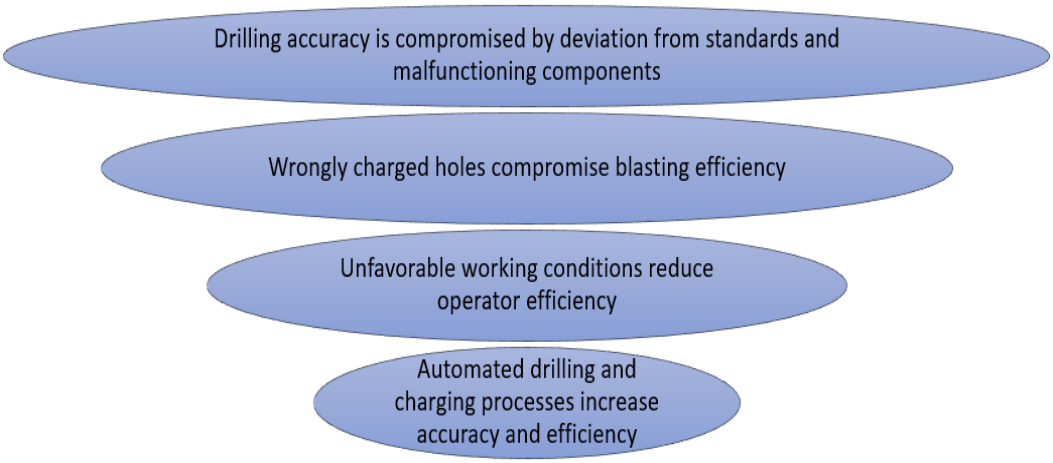


Figure 5-4: Influence of drilling and blasting practices on LHS performance

i. Deviations from drilling standards where collaring practices are flawed, rig feed and percussion pressures are wrong as well as the non-use of poly pipes and air drilling are a result of production pressures. Priority is placed on attaining meters per shift or day as compared to attaining quality blastable holes at the end of a round.

ii. The malfunctioning of machine components compromises drilling accuracy while machine breakdowns increase drilling cycles affecting stope turnaround time.

iii. Uncharged and short charged holes reduce the efficiency of the blast increasing the likelihood of under-break, while over charged holes pose the threat of over-break.

iv. Unfavourable working conditions (extreme heat and water logging) reduce the efficiency of operators who then aim to finish their marked holes and leave the working face without paying attention to the quality of the holes drilled.

v. The automated M6C drill rig is more efficient than the S7D drill rig and provides an option to track drilling operations through the reports it generates.

vi. The automated BME charging truck offers more accuracy and less strain on the charging team as compared to the manual K2 charging machine. The efficiency looks to improve as operators get more acquainted with the machine. The emulsion product from BME is however less preferred to that from AECL. A detailed study could provide insight into the most suitable product for South Deep Gold Mine.

5.1.4 Summary of findings

Figure 5-5 summarises the key findings relating to the study, showing the relative importance and individual contribution of each of the issues raised above.

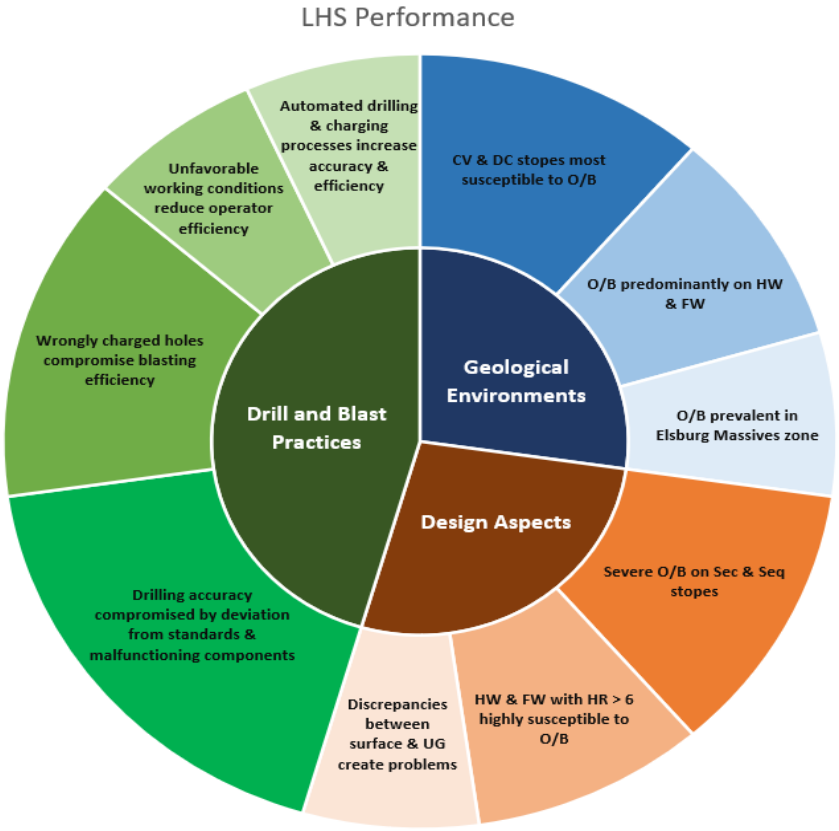


Figure 5-5: Relative importance of key findings

The study has further shown that these three factors investigated work in tandem to influence LHS performance. Above their individual contribution, any of their combination increases the impact on LHS performance. For instance, if a large dimension stope occurring under a de-stress cut environment and intersected on its boundaries by multiple reef horizons is drilled at deviated angles and overcharged, it will yield high over-break.

The study aimed to improve LHS performance by reducing the stope turnaround time. While no new stopes were evaluated for performance post analysis of the results, there is confidence that the recommendations from this study will significantly reduce stope turnaround time and improve LHS performance. Answering the research questions enabled the research to make positive strides in achieving its objectives of establishing empirical design charts and statistical models for different stoping scenarios, informing excavation design as well as reviewing drilling and blasting practices.

Although the research could not establish empirical design charts, it was able to formulate a stoping scenario matrix and calculator for predicting over-break performance and managing it. The charts and matrix represent the same phenomena but vary in visualization. Essentially, the study was able to formulate a solution that would guide in stope design given different stoping scenarios. It further generated a multi-variate model that would predict the amount of over-break given excavation dimensions for different stope surfaces.

Through the recommendations to follow, the research also met its objectives of informing excavation design and reviewing drilling and blasting practices at the mine. Despite having been untested on new stopes, there is confidence that the

proposed recommendations will limit the mine's over-break and under-break to no more than 30%.

Ultimately, the study has proven that mining environment-specific design and operational approaches can significantly improve LHS performance. The unique mining environments respond differently to excavation. It has further shown that the quality of drilling and blasting practices at the mine coupled with design aspects play a significant role in the performance of Long-hole stopes.

Correcting drilling and blasting practices, having harmonised (surface design and underground) stope design, and having the appropriate excavation dimensions will minimise the risk of poor LHS performance. In addition, the different levels of control from the matrix for managing over-break given the different stoping scenarios will further improve LHS performance mostly by reducing over-break.

5.2 Recommendations

Based on the presented findings, the research concludes by raising recommendations for implementation guided by a prioritization matrix presented in Figure 5-6 and those for further study to help improve LHS performance at South Deep.

5.2.1 Ready implementation

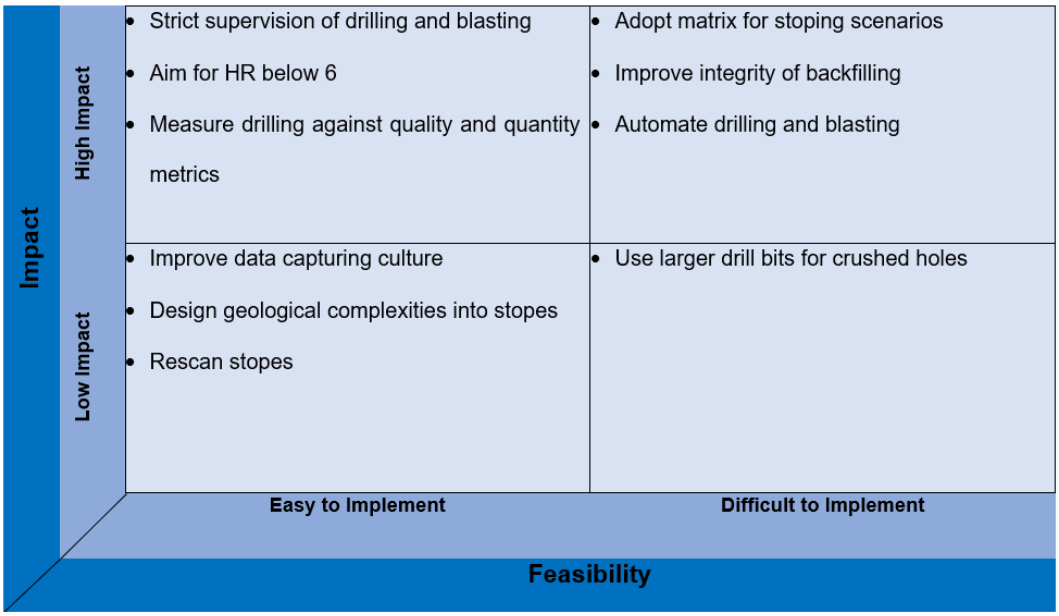


Figure 5-6: Recommendation prioritization matrix

i. The drilling and charging blueprints at the mine are sufficient to attain the desired fragmentation. Challenges arise in the implementation of these activities. There should be close and stricter supervision of these practices accompanied by short interval controls to ensure there are no deviations from standard practice.

ii. Drilling performance should be measured based on the quality of chargeable holes and adherence to standards compared to just meters drilled. The attainment of daily/shift targets must be marked against both quantity and quality metrics.

iii. In the designing of stopes, the stope spans should be such that they allow for hanging walls and footwalls to have hydraulic radius values of less than 6 to ensure they remain stable.

iv. The mine should adopt a hierarchy of controls for different stoping scenarios as guided by the matrix generated. This may vary from different standoff widths to excavation spans based on the mining environment.

v. As mining of most stopes progresses to secondary and sequential from primary, there is a need to increase the integrity of backfilling practices. Tight backfill will ensure the stability of future stopes and improve their performance.

vi. There should be an improvement in the data capturing culture at the mine to ensure all stope records are available and filed accordingly. This will enable continual improvement to be implemented as processes would be traceable. The application of machine learning particularly neural networks on data would boost performance prediction capabilities.

vii. To counter the impact of reef horizons and other geological complexities, these areas of weakness should be designed into the stope so that they are blasted together or if possible (within mineral resource and mineral reserve boundaries), avoided completely.

viii. The period between stope scanning, drill planning, and actual drilling should be minimised to cater for any possible movements of ground and changes in underground strata. If the period is extended, there should be rescanning of the stopes to ensure the design remains updated.

ix. The use of larger diameter drill bits and fewer holes for drilling crushed walls. This would ensure the blast shakes off the already unconsolidated ground and does not waste explosives.

x. The mine should consider the automation of both the processes of drilling and charging. Integrating automatic units to drilling will improve the accuracy and speed of drilling while allowing for appropriate tracking of performance and automating the charging process will lessen the physical burden on operators.

5.2.2 Further study

Considering that de-stress cut environments contribute the most to poor LHS performance, a review of the current or a new approach to de-stressing would be an area of interest in improving LHS performance. The high-profile de-stress method has been in effect from 2015 and its assessment could provide valuable insights to managing LHS performance at the mine. A review of the HR with consideration of the different geological environments could be another area worthy of further study to improve excavation geometry.

There were indications that some of the over-breaks recorded may have been a result of crush pillars collapsing with the blast. Whether planned or not, it would be justified to investigate the performance of all pillars at the mine and their influence on LHS performance. The study could also assess the suitability of the placement of sill pillars in large stopes for the control of hanging wall over-break as done by Chen and Mitri (2021).

REFERENCE LIST

Andrade, C. (2020) ‘Understanding the Difference Between Standard Deviation and Standard Error of the Mean, and Knowing When to Use Which’, *https://doi.org/10.1177/0253717620933419*, 42(4), pp. 409–410. Available at: https://doi.org/10.1177/0253717620933419.

Andrews, P. and Barsanti, B. (2008) ‘Results of the Radius Factor Stability Assessment Method for Design and Pillar Extraction at the Conqueror Mine, St Ives Gold Mine’, *SHIRMS 2008: First Southern Hemisphere International Rock Mechanics Symposium, 2008 16-19 September, Perth*, pp. 163–177. Available at: https://doi.org/10.36487/ACG_REPO/808_06.

Andrews, P.G., Butcher, R.J. and Ekkerd, J. (2020) ‘The Geotechnical Evolution of Deep-Level Mechanized Destress Mining at South Deep Mine’, *The Journal of the Southern African Institute of Mining and Metallurgy*, 120. Available at: https://doi.org/10.17159/2411.

Balanda, K.P. and Macgillivray, H.L. (1988) ‘Kurtosis: A critical review’, *American Statistician*, 42(2), pp. 111–119. Available at: https://doi.org/10.1080/00031305.1988.10475539.

Balt, K. and Goosen, R.L. (2020) ‘MSAHP: An approach to mining method selection’, *The Journal of the Southern African Institute of Mining and Metallurgy*, 120. Available at: https://doi.org/10.17159/2411.

Barrett, J.P. (2012) ‘The Coefficient of Determination—Some Limitations’, *http://dx.doi.org/10.1080/00031305.1974.10479056*, 28(1), pp. 19–20. Available at: https://doi.org/10.1080/00031305.1974.10479056.

Barton, N., Lien, R. and Lunde, J. (1974) ‘Engineering Classification of Rock Masses for the Design of Tunnel Support’, *Rock Mechanics Felsmechanik Mécanique des Roches*, 6(4), pp. 189–236. Available at: https://doi.org/10.1007/BF01239496.

Bigarre, P., Ben Slimane, K. and Tinucci, J. (1993) ‘3-Dimensional modelling of fault-slip rockbursting’, in Young (ed.) *3rd International Symposium on Rockbursts and Seismicity in Mines*. Kingston: A.A. Balkema, pp. 315–319.

Billaux, D. Chiles, J., Hestir, K. and Long, J. (1989) ‘Three-dimensional statistical modelling of a fractured rock mass—an example from the Fanay-Augères mine’, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 26(3–4), pp. 281–299. Available at: https://doi.org/10.1016/0148-9062(89)91977-3.

Bono, R., Arnau, J., Alarcon, R. and Bianca, M. (2019) ‘Bias, Precision, and Accuracy of Skewness and Kurtosis Estimators for Frequently Used Continuous Distributions’, *Symmetry 2020, Vol. 12, Page 19*, 12(1), p. 19. Available at: https://doi.org/10.3390/SYM12010019.

Brady, B.H.G. and Brown, E.T. (2004) *Rock Mechanics for Underground Mining*. 3rd edn. Boston, London: Kluwer Academic Publishers.

Brown, E.T., Green, S.J. and Sinha, K.P. (1981) *The Influence of Rock Anisotropy on Hole Deviation in Rotary Drilling A Review*, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*. Available at: https://www.sciencedirect.com/science/article/abs/pii/0148906281900036?fr=RR-2&ref=pdf_download&rr=88a57a899f5d0532 (Accessed: 15 October 2023).

Brownlee, J. (2018) *Basics of Linear Algebra for Machine Learning*. Available at: https://github.com/balban/Books/blob/master/Linear%20Algebra/Jason%20Brownlee-Basics%20for%20Linear%20Algebra%20for%20Machine%20Learning%20-%20Discover%20the%20Mathematical%20Language%20of%20Data%20in%20Python%20(2018).pdf (Accessed: 12 August 2022).

Bulbulia, T. (2018) 'Integrated mining software championed', *Mining Weekly*, 11 May. Available at: https://www.miningweekly.com/print-version/integrated-mining-software-championed-2018-05-11 (Accessed: 17 January 2024).

Cavanaugh, Joseph.E. and Neath, Andrew.A. (1999) 'Generalizing the deviation of the Schwarz information criterion', *Communications in Statistics - Theory and Methods* [Preprint].

Cepuritis, P. and Villaescusa, E. (2006) ‘Back Analysis Techniques for Assessing Open Stope Performance’, in *2006 Australian Mining Technology Conference ‘Value Through Cost Control’*. Hunter Valley, NSW: The Australiasian Institute of Mining and Metallurgy.

Chai, X.W., Shi, S., Yan, Y., Li. and Zhang, L. (2019) ‘Key blasting parameters for deep-hole excavation in an underground tunnel of phosphorite mine’, *Advances in Civil Engineering*, pp. 1–9. Available at: https://doi.org/10.1155/2019/4924382.

Chen, T. and Mitri, H.S. (2021) ‘Strategic sill pillar design for reduced hanging wall overbreak in longhole mining’, *International Journal of Mining Science and Technology*, 31(5), pp. 975–982. Available at: https://doi.org/10.1016/J.IJMST.2021.09.002.

Clark, L. and Pakalnis, R. (1997) ‘An Empirical Design Approach for Estimating Unplanned Dilution from Open Stope Hangingwalls and Footwalls’, in *99th Canadian Institute of Mining Annual Conference*. Vancouver, BC: CIM.

Copland, T. and Nehring, M. (2016) ‘Integrated Optimization of Stope Boundary Selection and Scheduling for Sublevel Stoping Operations’, *The Journal of the Southern African Institute of Mining and Metallurgy*, 116(12), pp. 1135–1142. Available at: https://doi.org/10.17159/2411-9717/2016/v116n12a7.

Dahlberg, E.C. and Griffiths, J.C. (1967) ‘Multivariate analysis of a sedimentary rock for evaluating effects of sedimentation processes’, *American Journal of Science*, 265(10), pp. 833–842. Available at: https://doi.org/10.2475/AJS.265.10.833.

Davison, A. and Forster, J. (2010) *Statistical Modelling*. Vaud. Available at: http://stat.epfl.ch,http://www.s3ri.soton.ac.uk.

Davison, A.C. (2008) *Cambridge Series in Statistical and Probabilistic Mathematics*. 1st edn. Edited by R. Gill et al. New York: Cambridge University Press.

de la Vergne, J. (2008) *Hard Rock Miner’s Handbook*. 5th edn. Edited by S. Andersen. Edmonton: Stantec Consulting. Available at: https://www.stantec.com/content/dam/stantec/files/PDFAssets/2014/Hard Rock Miner’s Handbook Edition 5_3.pdf (Accessed: 14 June 2021).

de Myttenaere, A., Golden, B., Le Grand, B. and Rossi, F. (2016) ‘Mean Absolute Percentage Error for regression models’, *Neurocomputing*, 192, pp. 38–48. Available at: https://doi.org/10.1016/J.NEUCOM.2015.12.114.

Fabozzi, F.J., Focardi, S., Rachev, S. and Arshanapalli, B. (2014) ‘Appendix E: Model Selection Criterion: AIC and BIC’, in *The Basics of Financial Econometrics*. Wiley, pp. 399–403. Available at: https://doi.org/10.1002/9781118856406.app5.

Feizi, F., Amir Abbas Karbalaei-Ramezanali and Farhadi, S. (2021) ‘Application of multivariate regression on magnetic data to determine further drilling site for iron exploration’, *Open Geosciences*, 13(1), pp. 138–147. Available at: https://doi.org/10.1515/GEO-2020-0165/MACHINEREADABLECITATION/RIS.

Ghasemi, Y. (2012) ‘Numerical studies of mining geometry and extraction sequencing in Lappberget, Garpenberg’.

Gill, D.E., Aubertin, M. and Simon, R. (1993) ‘A practical engineering approach to the evaluation of rockburst potential.’, in *3rd International Symposium on Rockbursts and Seismicity in Mines*. Kingston: A.A. Balkema, pp. 63–68.

Gold Fields (2011) *Gold Fields: Mineral Resources and Mineral Reserves Supplement*. Johannesburg. Available at: https://www.goldfields.com/reports/ar_dec_2011/minerals/index.php (Accessed 15 February 2022)

Gold Fields (2013) ‘Overview of the South Deep Project’. Available at: https://www.goldfields-southdeep.co.za/about-us/about-south-deep/overview#:~:text=South%20Deep%20Gold%20Mine%20is,Johannesburg%2C%20South%20Africa's%20commercial%20capital. (Accessed 15 February 2022)

Gold Fields (2017) ‘Gold Fields South Deep Rebase Plan Market Presentation’. Johannesburg: Gold Fields. Available at:

https://www.goldfields.com/pdf/investors/presentation/2017/south-deep-rebase-plan/presentation.pdf (Accessed: 8 July 2021).

Gold Fields (2020) *The Gold Fields Mineral Resources and Mineral Reserves Supplement to the Integrated Annual Report*. Available at: https://www.goldfields.com/pdf/investors/integrated-annual-reports/2020/mmr-2020.pdf (Accessed: 25 July 2022)

Gold Fields (2021) *Drilling and Blasting-Stope Health Report*.

Gold Fields (2022a) *Gold Fields South Deep Gold Mine - Geology*. Available at: https://www.goldfields-southdeep.co.za/about-us/about-south-deep/geology (Accessed: 2 June 2022).

Gold Fields (2022b) *Gold Fields South Deep Gold Mine - History*. Available at: https://www.goldfields-southdeep.co.za/about-us/about-south-deep/history (Accessed: 2 June 2022).

Gold Fields (2022c) *Gold Fields South Deep Gold Mine - How we mine*. Available at: https://www.goldfields-southdeep.co.za/about-us/about-south-deep/how-we-mine (Accessed: 2 June 2022).

Granian, H., Tabatabael, S., Asadi, H. and Carranza, E. (2015) 'Multivariate regression analysis of lithogeochemical data to model subsurface mineralization: A case study from the Sari Gunay epithermal gold deposit, NW Iran', *Journal of Geochemical Exploration*, 148, pp. 249–258. Available at: https://doi.org/10.1016/J.GEXPLO.2014.10.009.

Hamrin, H. (1982) ‘General Mine Design Considerations’, in *Underground Mining Methods - Engineering Fundamentals and International Cases*. New York: SME-AIME, pp. 88–112. Available at: http://www.ct.ufrgs.br/laprom/Underground Mining Methods.pdf.

Harris, P. and Wesseloo, J. (2015) ‘mXrap’. Perth: Australian Centre for Geomechanics. Available at: https://mxrap.com/ (Accessed: 11 January 2022).

Hartman, H.L. (1992) *SME Mining Engineering Handbook, Third Edition*. 2nd edn. Edited by J.M. Mutmansky et al. Colorado: Society for Mining, Metallurgy, and Exploration (SME Mining Engineering Handbook).

Hartman, H.L. and Mutmansky, J.M. (2002) *Introductory Mining Engineering*. 2nd edn. John Wiley & Sons.

Hedley, D.G.F. (1992) *Rockburst Handbook for Ontario Hardrock Mines*. Ottawa.

Heidarzadeh, S. (2018) *Probabilistic Stability Analysis of Open Stopes in Sublevel Stoping Method by Numerical Modelling*. PhD. University of Quebec at Chicoutimi. Available at: https://core.ac.uk/download/pdf/199238804.pdf.

Heidarzadeh, S., Saeidi, A. and Lavoie, C. (2021) ‘Geochemical Characterisation of Heterogeneous Rock Mass using Geological and Laboratory Test Results: A Case Study of the Niobec Mine, Quebec (Canada)’, *SN Applied*

Sciences, 3(6), pp. 1–20. Available at: https://doi.org/10.1007/s42452-021-04617-1.

Hempkins, W.B. (1969) *Mathematical and statistical models for prediction of ore distribution patterns in mines of the Witwatersrand Basin, South Africa*. PhD. Northwestern University.

Henley, S.S., Golden, R.M. and Kashner, T.M. (2020) 'Statistical modeling methods: challenges and strategies', *Biostatistics and Epidemiology*, 4(1), pp. 105–139. Available at: https://doi.org/10.1080/24709360.2019.1618653.

Henning, J.G. (2007) *Evaluation of Long-Hole Mine Design Influences on Unplanned Ore Dilution*. PhD. McGill University. Available at: https://core.ac.uk/download/pdf/41887398.pdf (Accessed: 14 June 2021).

Hessing, T. (2018) *F Distribution, F Statistic, F Test*. Available at: https://sixsigmastudyguide.com/f-distributionf-statistic-f-test/ (Accessed: 9 March 2023).

Hinz, J., Grigoryev, I. and Novikov, A. (2020) 'An application of high-dimensional statistics to predictive modeling of grade variability', *Geosciences (Switzerland)*, 10(4). Available at: https://doi.org/10.3390/geosciences10040116.

Hustrulid, W.A. (1971) 'The percussive drilling of quartzite', *Journal of the South African Institute of Mining and Metallurgy*, pp. 245–268.

Ibarra, J.A., Maerz, N.H. and Franklin, J.A. (1996) ‘Overbreak and Underbreak in Underground Openings Part 2: Causes and Implications’, *Geotechnical and Geological Engineering*, 14(4), pp. 325–340. Available at: https://doi.org/10.1007/BF00421947.

Idris, M.A. (2014) *Probabilistic Stability Analysis of Underground Mine Excavations*. PhD. The Lulea University of Technology. Available at: http://www.diva-portal.org/smash/get/diva2:991342/FULLTEXT01.pdf.

Jager, A.J. and Ryder, J.A. (1999) *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines*. 1st edn. Braamfontein, Johannesburg: Safety in Mines Research Advisory Committee.

Joughin, W., Armstrong, R. and Waldeck, W. (2006) *Evaluation of the critical mining span based on the hydraulic radius concept and evaluation of the mining sequence for 95 1W long hole stopes*. Johannesburg.

Kenda, K., Peternelj, J, Mellios, N., Kofinas, D., Cerin, M. and Rozanec, J. (2020) ‘Usage of statistical modeling techniques in surface and groundwater level prediction’, *Journal of Water Supply: Research and Technology - AQUA*, 69(3), pp. 248–265. Available at: https://doi.org/10.2166/aqua.2020.143.

Kenton, W. (2022) *Standard Error (SE) Definition: Standard Deviation in Statistics Explained*. Available at: https://www.investopedia.com/terms/s/standard-error.asp (Accessed: 11 March 2023).

Kirk, J., Ruiz, J., Chesley, J. and Titley, S. (2003) ‘The origin of gold in South Africa’, *American Scientist*, 91(6), pp. 534–541. Available at: https://doi.org/10.1511/2003.38.907.

Knoll, P. and Kuhnt, W. (1990) ‘Investigation of the mechanism of rock bursts by seismological measurements’, in *Rockbursts, Global Experiences*. Rotterdam: A.A. Balkema, pp. 11–36.

Konicek, P. and Schreiber, J. (2018) ‘Rockburst prevention via destress blasting of competent roof rocks in hard coal longwall mining’, *The Journal of the Southern African Institute of Mining and Metallurgy*, 118(3), pp. 235–242. Available at: https://doi.org/10.17159/2411-9717/2018/v118n3a6.

Larsson, K. (2004) *Seismicity in Mines - A Review*. Lulea.

Malan, D.F. (2003) ‘Guidelines for Measuring and Analysing Continuous Stope Closure Behaviour in Deep Tabular Excavations’. Braamfontein, Johannesburg: Safety in Mines Research Advisory Committee (SIMRAC). Available at: https://researchspace.csir.co.za/dspace/bitstream/handle/10204/1283/GAP852 guideline.pdf?sequence=1 (Accessed: 20 May 2021).

Masniyom, M. (2009) *Systematic Selection and Applications of Backfill in Underground Mines*. PhD. TU Bergakademie Freiberg.

Mathews, K.E., Hoek, E., Wyllie, D. and Stewart, S. (1981) 'Prediction of Stable Excavation Spans for Mining at Depths below 1000 Meters in Hard Rock'. Ottawa: Canada Center for Mining and Energy Technology.

Mawdesley, C., Trueman, R. and Whiten, W.J. (2001) 'Extending the Mathews Stability Graph for Open-Stope Design', *Institution of Mining and Metallurgy. Transactions. Section A: Mining Technology*, 110(1), pp. 27–39. Available at: https://doi.org/10.1179/mnt.2001.110.1.27.

McAlevey, L.G. and Stent, A.F. (2017) 'Kurtosis: a forgotten moment', *https://doi.org/10.1080/0020739X.2017.1357848*, 49(1), pp. 120–130. Available at: https://doi.org/10.1080/0020739X.2017.1357848.

McFadyen, B. *et al.* (2020) 'A new stope reconciliation approach', in. Australian Centre for Geomechanics, pp. 335–350. Available at: https://doi.org/10.36487/acg_repo/2035_17.

Microsoft Corporation (2021) 'Microsoft Excel'. Available at: https://office.microsoft.com/excel (Accessed: 20 August 2021).

More O'ferrall, G.C. and Du Plessis, M. (2017) *The influence of Geological Structures-an often-overlooked important aspect affecting the stability of operating mines*, *Cape Town Southern African Institute of Mining and Metallurgy*.

Obermeyer, P.G. (2005) *Stratigraphy of South Deep - A Description*. Johannesburg.

Obermeyer, P.G. (2020) *Evidence of basin partitioning in the UE7 and upper Elsburg massives of the Turffontein subgroup, Witwatersrand basin (South Africa)*. Master of Science. University of the Witwatersrand.

Ortlepp, W.D. (1997) *Rock Fracture and Rockbursts: An illustrative study*. Southern African Institute of Mining and Metallurgy.

Osburn, K., Pretorius, H., Kock, D., King, N., Pillaye, R. and Hlangwane, M. (2014) 'Enhanced geological modelling of the Upper Elsburg reefs and VCR to optimize mechanized mine planning at South Deep Gold Mine', *Journal of the Southern African Institute of Mining and Metallurgy*, 114(3), pp. 275–283. Available at: http://www.scielo.org.za/pdf/jsaimm/v114n3/18.pdf (Accessed: 24 May 2022).

Ozbay, M.U., Ryder, J.A. and Jager, A.J. (1995) 'The design of pillar systems as practised in shallow hard-rock tabular mines in South Africa', *The Journal of the Southern African Institute of Mining and Metallurgy*, 95(1), pp. 7–18.

Pandey, R., Thote, N. and Singh, T. (2011) 'Development of statistical model for prediction of occupational noise exposure to SDL operators in Indian underground coal mines', *Noise and Vibration Worldwide*, 42(5), pp. 8–12. Available at: https://doi.org/10.1260/0957-4565.42.5.8.

Papaioanou, A. and Suorineni, Fidelis.T. (2015) 'Development of a Dilution-based Stability Graph for Open Stope Design', *Mining Education Australia*

- *Research Projects Review*, pp. 27–33. Available at: https://www.researchgate.net/publication/277022455.

Pontow, S. (2019) *Evaluation of Methods for Stope Design in Mining and Potential of Improvement by Pre-Investigations*. Masters. Aalto University. Available at: https://aaltodoc.aalto.fi/bitstream/handle/123456789/40907/master_Pontow_Sebastian_2019.pdf?isAllowed=y&sequence=2.

Potvin, Y. (1988) *Empirical Open Stope Design in Canada*. PhD. University of British Columbia. Available at: https://doi.org/10.14288/1.0081130.

Potvin, Y. and Hudyma, M. (2000) 'Open Stope Mining in Canada', in *Proceedings of the MassMin2000*. Brisbane, Australia: Australasian Institute of Mining and Technology, pp. 661–674. Available at: https://www.ausimm.com/publications/conference-proceedings/massmin-2000/open-stope-mining-in-canada/.

Python Software Foundation (2022) 'Python'. Available at: http://www.python.org/ (Accessed: 6 December 2022).

Qi, C. and Fourie, A. (2019) 'Cemented paste backfill for mineral tailings management: Review and future perspectives', *Minerals Engineering*, 144. Available at: https://doi.org/10.1016/J.MINENG.2019.106025.

Quaye, G.B. and Guler, G. (1998) 'The importance of both geological structures and mining induced stress fractures on the hangingwall stability in a deep

level gold mine', *The Journal of the Southern African Institute of Mining and Metallurgy*, pp. 157–162.

Rankine, R., Pacheco, M. and Sivakugan, N. (2007) 'Underground mining with backfills', *Soils and Rocks*, 30(2), pp. 93–101. Available at: https://doi.org/10.28927/SR.302093.

Rapson, G. and Rupprecht, S. (2004) 'Long hole drilling for the platinum industry – a mining perspective', *The Journal of the Southern African Institute of Mining and Metallurgy*, pp. 177–186.

Safanov, Y.G. and Prokof'ev, V.Y. (2006) 'Gold-bearing reefs of the Witwatersrand Basin: A model of synsedimentation hydrothermal formation', *Geology of Ore Deposits*, 48, pp. 415–447.

Schafer, Lindsey.A. (2018) *Statistical Analysis of Mining Parameters to Create Empirical Models to Predict Mine Pool Formation in Underground Coal Mines*. Masters. Ohio University.

Scott, D.F. (1988) 'Relationship of geological features to seismic events, Lucky Friday Mine, Mullan, Idaho', in Fairhurst (ed.) *2nd International Symposium on Rockbursts and Seismicity in Mines*. Minneapolis: A.A. Balkema, pp. 401–405.

Scott, D.F., Williams, T.J. and Friedel, M.J. (1997) 'Investigation of a rockburst site, Sunshine Mine, Kellogg, Idaho', in Gibowicz (ed.) *4th International Symposium on Rockbursts and Seismicity in Mines*, pp. 311–315.

Sewnun, D., Joughin, W., Armstrong, R. and Cooper, A. (2018) 'Keyblock Stability Analysis of Longhole Stopes', *Journal of the Southern African Institute of Mining and Metallurgy*, 118(3), pp. 243–250. Available at: https://doi.org/10.17159/2411-9717/2018/v118n3a7.

Sheshpari, M. (2015) 'A review of underground mine backfilling methods with emphasis on cemented paste backfill', *Electronic Journal of Geotechnical Engineering*, 20(13), pp. 5183–5208. Available at: https://www.researchgate.net/publication/282307412_A_review_of_underground_mine_backfilling_methods_with_emphasis_on_cemented_paste_backfill (Accessed: 14 June 2022).

Singh, S.P. (2018) 'Over Break Control in Underground Mines', *MOJ Civil Engineering*, 4(5), pp. 429–435. Available at: https://doi.org/10.15406/mojce.2018.04.00140.

Stacey, T. (2001) *Best Practice Rock Engineering Handbook for 'Other' Mines*. 1st edn. Johannesburg: SRK Consulting. Available at: https://www.sanire.co.za/sanire-documents/textbooks/660-best-practice-rock-engineering-handbook-for-other-mines-handbook/file.

Suorineni, F.T. (2010) 'The Stability Graph After Three Decades in Use: Experiences and the Way Forward', *International Journal of Mining, Reclamation and Environment*, 24(4), pp. 307–339. Available at: https://doi.org/10.1080/17480930.2010.501957.

Suorineni, F.T., Hebblewhite, B. and Saydam, S. (2014) ‘Geomechanics challenges of contemporary deep mining: a suggested model for increasing future mining safety and productivity’, *The Journal of the Southern African Institute of Mining and Metallurgy*, 114, pp. 1023–1032.

Suorineni, F.T., Tannant, D.D. and Kaiser, P.K. (1999) ‘Determination of fault-related sloughage in open stopes’, *International Journal of Rock Mechanics and Mining Sciences*, 36(7), pp. 891–906. Available at: https://doi.org/10.1016/S0148-9062(99)00055-8.

Taylor, S. (2023) *Covariance - Definition, Formula, and Practical Example*. Available at: https://corporatefinanceinstitute.com/resources/data-science/covariance/ (Accessed: 11 March 2023).

Tommila, E. (2014) ‘Mining method evaluation and dilution control in Kittilä mine’. Available at: www.aalto.fi (Accessed: 1 July 2022).

Tshabalala, M and Pretorius, Jhc (2021) ‘Quality and Reliability Analysis of Long-hole Stope Slots: A Case Study at South Deep Gold Mine Based on Drilling and Blasting Practices’, in Mzwakhe Tshabalala and JHC. Pretorius (eds) *International Conference on Industrial Engineering and Operations Management*. Monterrey: IEOM.

Tucker, R.F., Viljoen, R.P. and Viljoen, M.J. (2016) ‘A Review of the Witwatersrand Basin - The World’s Greatest Goldfield’, *Episodes Journal of International Geoscience*, 39(2), pp. 104–133.

Vervoot, A. and Moyson, D. (1997) ‘Steel fibre reinforced shotcrete: An adequate support for rockburst conditions?’, in Gibowicz and Lasocki (eds) *4th International Symposium on Rockbursts and Seismicity in Mines*. Rotterdam: A.A. Balkema, pp. 355–359.

Villaescusa, E. (2003) *Global extraction sequences in sublevel stoping*. Available at: https://docplayer.net/124540964-Global-extraction-sequences-in-sublevel-stoping-mpes-2003-conference-kalgoorlie-april-ernesto-villaescusa-professor-of-mining-geomechanics.html (Accessed: 1 July 2022).

Wagner, H. (2009) ‘Deep Mining: A Rock Engineering Challenge’, *Rock Mechanics and Rock Engineering*, 1, p. 3. Available at: https://doi.org/10.1007/s00603-019-01799-4.

Wang, J., Milne, D., Wegner, L. and Reeves, M. (2007) ‘Numerical evaluation of the effects of stress and excavation surface geometry on the zone of relaxation around open stope hanging walls’, *International Journal of Rock Mechanics and Mining Sciences*, 44(2), pp. 289–298. Available at: https://doi.org/10.1016/j.ijrmms.2006.07.002.

Watson, B.P., Pretorius, W., Mpunzi, P., du Plooy, M., Matthysen, K. and Kuijpers, J. (2014) ‘Design and Positive Financial Impact of Crush Pillars on Mechanized Deep-Level Mining’, *The Journal of The Southern African Institute of Mining and Metallurgy*, 114(10), pp. 863–873. Available at:

https://www.saimm.co.za/Journal/v114n10p863.pdf (Accessed: 22 June 2021).

White, A., Lawler, I. and Romer, W. (2008) ‘Deswik’. Perth: Deswik Mining Consultants Pty Ltd. Available at: https://www.deswik.com/software/ (Accessed: 23 October 2022).

Xie, J., Xu, J. and Wang, F. (2018) ‘Mining-induced stress distribution of the working face in a kilometer-deep coal mine—a case study in Tangshan coal mine’, *Journal of Geophysics and Engineering*, 15(5), pp. 2060–2070. Available at: https://doi.org/10.1088/1742-2140/AABC6C.

Yang, Y. (2003) *Can the Strengths of AIC and BIC Be Shared?* Department of Statistics, Iowa State University. Available at: http://users.stat.umn.edu/~yangx374/papers/Pre-Print_2003-10_Biometrika.pdf (Accessed: 3 February 2023).

Yi, X. and Kaiser, P. (1993) ‘Mechanism of rock mass failure and prevention strategies in rockburst conditions’, in Young (ed.) *3rd International Symposium on Rockbursts and Seismicity in Mines*. Kingston: A.A. Balkema, pp. 141–145.

Yowa, G.G. (2018) ‘Different back fill materials used in underground mines’, *Basic Mining Techniques Blog* [Preprint]. Available at: https://www.pngminers.com/2018/04/different-back-fill-materials-used-in.html (Accessed: 14 June 2022).

Yuan, K.H., Bentler, P.M. and Zhang, W. (2005) ‘The Effect of Skewness and Kurtosis on Mean and Covariance Structure Analysis’, *http://dx.doi.org/10.1177/0049124105280200*, 34(2), pp. 240–258. Available at: https://doi.org/10.1177/0049124105280200.

Zhang, L., Hu, J., Wang, X. and Zhao, L. (2018) ‘Optimization of Stope Structural Parameters Based on Mathews Stability Graph Probability Model’, *Advances in Civil Engineering*, 2018. Available at: https://doi.org/10.1155/2018/1754328.

APPENDICES

Appendix A: Stope Database

						STOPE TOTAL							Mining Environment	
Recon Date	Reef Surface Block	Stope Name	Length (m)	Width (m)	Height (m)	Stope Volume (m^3)	Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Dimension Factor %	DESWIK VISUAL	STOPE CLASSIFICATION	Stope Above (DC, CV, LV, OS, OD, SL)	Reef Contact Package
Jan-18	2D	100 4W CUT2 LH04A	43	19	17	6205	2156	34.75%	1664	26.82%	7.94%	Good	SEC	DC	MBT, VCR, ECMC, MB
Nov-20	2D	95 3W CUT05 LPIL 01W	80	21	27	13944	4829	34.63%	642	4.60%	39.61%	Good	SEC	LV	, MAC, MAD, MBT, V
Feb-18	1A	87 1W BW LH11	28	16	23	3322	735	22.14%	975	29.34%	-7.20%	Good	PRI	CV	N/A
Jun-18	2D	100 4W CUT3 LH10A	22	17	19	2622	1665	63.52%	1141	43.52%	20.01%	Good	PRI	LV	ECB, VCR, MIT
Feb-18	2C	95 2W MP7 LHS1E	25	17	14	2415	872	36.12%	132	5.45%	30.67%	Good	PRI	DC	MBBTR, MIBTR, MIQT
Jun-18	1C	095 1W CUT3 LHS 09B	56	15	23	8704	2644	30.37%	2411	27.70%	2.67%	Good	SEC	SL	MBB
Jun-18	1A	87 1W B18 LHS03	43	11	22	3475	548	15.77%	3292	94.72%	-78.95%	Good	PRI	CV	N/A
Oct-21	1C	95 1W CUT04 LHS 07N	65	25	43	6529	2657	40.69%	630	9.65%	31.05%	Good	SEQ	DC	MIT, MBT
Sep-18	2E	100 4W CUT3 LH07 MB	42	20	20	6125	915	14.93%	3341	54.54%	-39.61%	Good	PRI	LV	MAD, MBT, MIT, VCR
Oct-21	2D	95 3W CUT03 LPIL 05W	37	16	21	4795	1640	34.20%	112	2.34%	31.86%	Good	PRI	OD	MBB, ECMC, ED, MA
Jun-20	2D	100 04W CUT02_LHP 08N	43	12	25	9420	3677	39.03%	657	6.97%	32.06%	Good	PRI	OS	ECB, MAD
Apr-20	2E	100 4W CUT2 LHS 05E	38	13	18	4140	1692	40.87%	348	8.41%	32.46%	Good	PRI	DC	ED, MBB, MIB
May-20	1C	90 1W CUT2 LHS 06W	35	16	27	6056	2435	40.22%	419	6.91%	33.30%	Good	SEC	DC	MBB, MBT,MIB
Jun-19	1C	095 1W CUT3 LHS06B	52	16	16	5789	818	14.14%	838	14.47%	-0.34%	Good	PRI	SL	MBB
Jan-20	2D	095 02W MPR08_LHS_04W	29	11	16	1881	984	52.31%	481	25.54%	26.77%	Good	SEC	LV	MAD,MBB, MIT, VCR
Jun-18	1C	090 1W CUT02 LHS 5A	19	14	24	5110	2431	47.57%	644	12.60%	34.97%	Good	PRI	DC	MIT, MIB, MBT
Oct-21	2G	100 2AW CUT03 LHS 01E	86	30	27	30,823.821	12332	40.01%	1478	4.80%	35.21%	Good	SEQ	SL	MBT, MIQ
Feb-20	1C	90 1BW CUT2 LHS 04W	20	14	20	4790	1863	38.89%	740	15.44%	23.45%	Good	SEQ	DC	MAD, MIQ
Feb-21	2E	100 4W CUT03 LPIL 01N-C	66	22	36	15216	6392	42.01%	980	6.44%	35.57%	Good	SEC	LV	MC, VCR, MIT, MBT,
Mar-21	2D	100 4W CUT01 LHQS 01E	20	16	14	1501	1012	67.42%	476	31.70%	35.72%	Good	SEQ	LV	MBB, MBT, VCR
Mar-20	2C	095 02W MPR04_LHS_01N	44	21	37	10569	3895	36.85%	891	8.43%	28.42%	Good	PRI	OS	CBATR, ECMQ, ED, E
Mar-20	2D	95 3W MPR07 LPIL 11S	98	23	20	10381	4168	40.16%	1201	11.57%	28.59%	Good	PRI	LV	ED, MAC, MBB, VCR
Sep-21	2C	95 2W CUT07 LHS 01E	23	18	13	1789	689	38.52%	43	2.43%	36.09%	Good	SEC	LV	MBTTR, MIQTR
Mar-20	2G	100 2BW CUT03_LHP_01W	43	20	37	10620	4189	39.44%	268	2.53%	36.92%	Good	PRI	DC	MBT, VCR, MIQ
May-20	2D	100 4W CUT1 LHP 02E	25	15	18	2651	745	28.11%	305	11.52%	16.58%	Good	SEC	SL	MBB, MBT
Aug-20	1C	95 1W CUT3 LHS 07B	59	14	25	12177	5314	43.64%	811	6.66%	36.98%	Good	SEC	LV	MIT, MBT
Nov-21	1C	90 1W CUT02 LHS 04B	64	33	29	18202	7932	43.58%	1150	6.32%	37.26%	Good	PRI	DC	MIB, MBT, MIT
Jun-20	1DEF	100 1BW CUT3 LHQ 05W	60	12	14	3692	900	24.38%	463	12.55%	11.83%	Good	SEC	SL	MBT, MIQ, MIT
Aug-20	2D	95 3W CUT05 LHP 01W	33	19	23	5923	2376	40.11%	156	2.63%	37.49%	Good	PRI	DC	, MAC, MAD, MBT, V
Aug-20	2E	100 4W CUT4 LHQ 06E	30	17	24	5724	1375	24.02%	936	16.35%	7.67%	Good	SEQ	DC	MAC, ED, ECMC, ECB
Jul-21	1C	95 1W CUT04 LHS 07B	25	20	43	10224	4540	44.40%	665	6.50%	37.90%	Good	PRI	OD	VCR, MBB, MBT
Sep-21	2D	100 4W CUT03 LHQ 05W	77	17	27	15923	6968	43.76%	901	5.66%	38.11%	Good	SEC	DC	MAC, MBB,MBT
Sep-20	1DEF	100 1BW CUT03 LHQS 06E	30	26	19	8850	2845	32.15%	567	6.41%	25.74%	Good	SEQ	DC	MIT, MBT, MBB
Jan-20	2C	95 2W MP04 LHS 03W	25	13	18	4702	2597	55.23%	705	14.99%	40.24%	Good	PRI	CV	BATR, ECBTR, ECMC
Jan-21	2F	100 3W CUT03 LHS 04W	19	9	16	1011	242	23.91%	385	38.06%	-14.15%	Good	PRI	SL	ED, MAC, MIB
Apr-19	1C	90 1W Cut2 LH 7A	42	22	25	8119	4001	49.28%	685	8.43%	40.85%	Good	PRI	DC	MIB, MBT
Mar-21	2D	100 4W CUT02 LHQ 07E	26	12	28	3363	1106	32.89%	268	7.95%	24.94%	Good	SEQ	DC	MBB, ECB, ECMC
Sep-18	1DEF	100 1BW CUT3 LHS03B	49	24	32	14644	7670	52.37%	1559	10.64%	41.73%	Good	SEC	DC	MBT
Apr-21	2E	95 2W CUT01 LHQS 03W	34	14	20	7156	2573	35.96%	705	9.85%	26.11%	Good	SEQ	OS	MAD, MBT, MIQ, MIT,
Apr-21	1C	95 1W CUT03 LHQ 07N	90	20	22	20939	6669	31.85%	2036	9.72%	22.12%	Good	PRI	SL	MBB, MBT, MIT
May-21	2F	100 3W CUT03 LHQ 03E	33	15	25	4786	864	18.06%	1683	35.17%	-17.11%	Good	SEQ	LV	MIQ
May-21	2E	100 4W CUT04 LHS 05E	56	22	27	11162	2288	20.50%	1259	11.28%	9.22%	Good	SEC	OD	ECT,MAC
May-21	2F	100 3W CUT03 LHS 01E	25	15	27	3894	953	24.47%	285	7.32%	17.16%	Good	SEC	DC	MAC,MAD, MBT, MIQ,
May-21	2D	95 3W CUT05 LPIL 03W	24	21	15	2689	1021	37.97%	297	11.05%	26.92%	Good	SEC	LV	CT, MAC, MBB, ECMC
Jun-21	1DEF	100 1BW CUT03 LHQ 03W	54	30	30	16911	5534	32.73%	967	5.72%	27.01%	Good	SEQ	DC	MBT
Jun-21	2F	100 3W CUT03 LHQ 03W	15	13	19	3108	840	27.02%	160	5.14%	21.89%	Good	SEQ	OD	ECMQ, ED, MAD, MIT
Jul-21	2E	95 2W CUT03 LHS 01S	44	22	12	2560	641	25.04%	311	12.15%	12.90%	Good	SEQ	SL	MBTTR
Sep-18	1A	87 1W B04 LHS08	35	26	35.8	16625	8683	52.22%	1533	9.22%	43.00%	Good	PRI	CV	ED, MAC, MAD
Aug-21	1C	90 1W CUT01 LHS 07E	33	13	9	1,211	222	18.32%	697	57.55%	-39.23%	Good	PRI	SL	MIB
Feb-19	2E	100 4W CUT3 LHS04C	30	17	25	5371	2806	52.24%	379	7.06%	45.18%	Good	SEC	DC	MAC, MAD, MBT, VCR
Aug-20	1C	90 1W CUT2 LHS 08W	33	14	22	3859	2102	54.49%	262	6.79%	47.70%	Good	SEC	DC	MBT, MIT
Sep-21	2G	100 2AW CUT04 LHQ 01E	32	21	48	4904	1351	27.55%	224	4.57%	22.98%	Good	PRI	OD	MAC, MBB, MBT, MIC
Mar-20	1DEF	100 1BW CUT3 LHS 1A	86	16	23	19493	10697	54.88%	1026	5.26%	49.62%	Good	SEC	DC	MBT
Jun-18	2D	90 3W LHS09	39	22	26	10571	6563	62.09%	546	5.17%	56.92%	Good	PRI	CV	ECBA, ECMC, ED,MA
Dec-21	2E	100 4W CUT04_LHQS 10E	37	24	24	9549	5814	60.88%	324	3.39%	57.49%	Good	SEQ	DC	MBB, ECB
Oct-21	2C	95 2W CUT08 LHSS 05N	108	23	30	18534	5100	27.52%	1942	10.48%	17.04%	Good	SEC	SL	MACTR,MITTR,MBBT
May-20	2D	90 3W CUT2 LHP 11E	18	16	26	1237	901	72.84%	14	1.12%	71.73%	Good	SEC	CV	ECBA, MAC, ED, ECM
Nov-21	1C	95 1W CUT03 LHS 10B	75	16	27	8365	3699	44.23%	1260	15.06%	29.17%	Good	SEQ	SL	MBB, MBT
Dec-21	1DEF	100 1BW CUT04 LHS 07W	58	22	40	19078	5654	29.63%	1125	5.90%	23.74%	Good	PRI	OD	MBT, MIT
Feb-20	2G	100 2AW CUT3 LPIL 8 N	33	16	7	959	293	30.53%	4	0.42%	30.11%	Good	PRI	LV	MBT

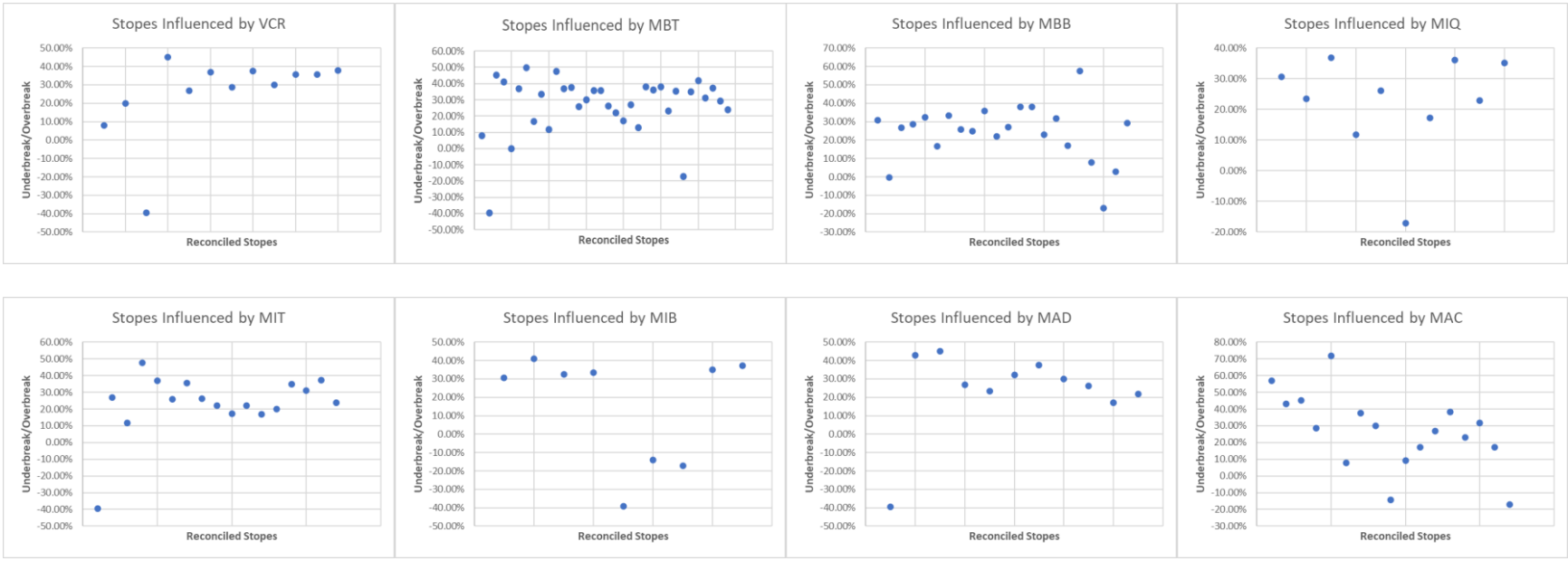
Appendix B: Stope Surface Database

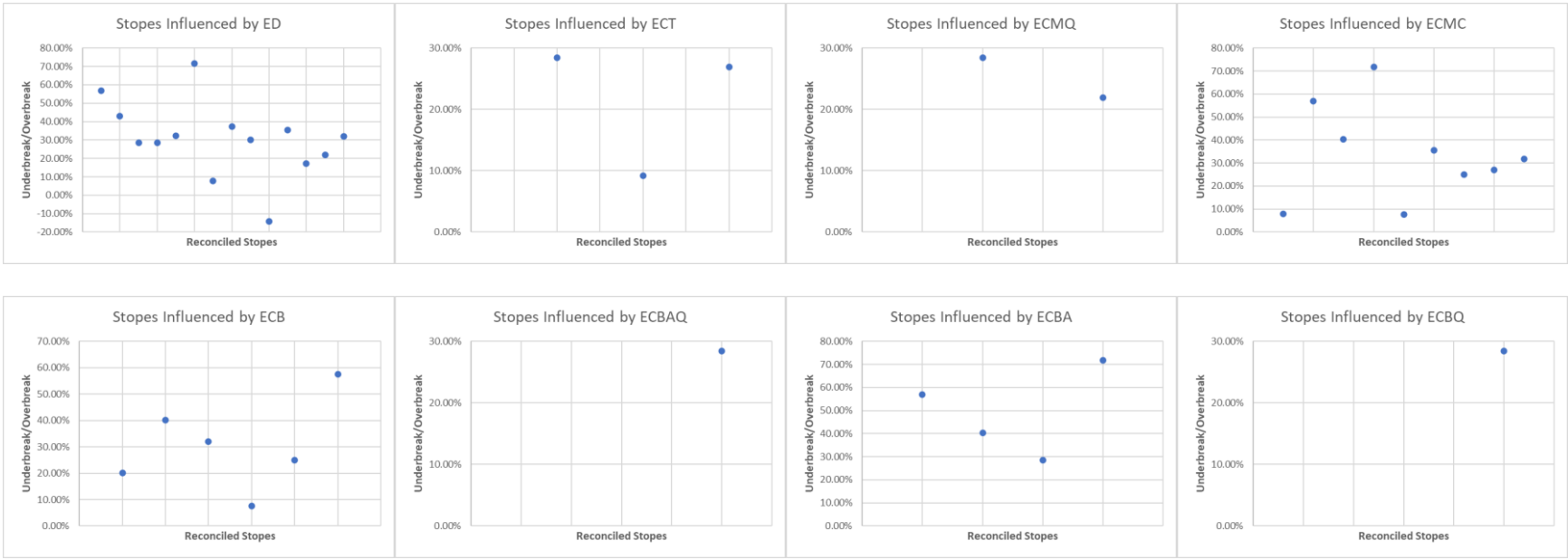
CROWN						HANGING WALL						FOOT WALL						SIDE WALL 1						SIDE WALL 2					
Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Difference %	HR	Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Difference %	HR	Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Difference %	HR	Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Difference %	HR	Overbreak (m^3)	Overbreak %	Underbreak (m^3)	Underbreak %	Difference %	HR
266	4%	0	0%	4%	7	1444	23%	775	12%	11%	6	443	7%	724	12%	-5%	6	3	0%	58	1%	-1%	5	0	0%	107	2%	-2%	5
253	2%	0	0%	2%	8	2343	17%	377	3%	14%	10	2227	16%	265	2%	14%	10	2	0%	0	0%	0%	6	4	0%	0	0%	0%	6
210	6%	27.3	1%	5%	5	428	13%	228	7%	6%	6	58	2%	711	21%	-20%	6	21	1%	0	0%	1%	5	18	1%	8	0%	0%	5
121	5%	0	0%	5%	5	1001	38%	376	14%	24%	4	441	17%	619	24%	-7%	4	9	0%	147	6%	-5%	5	94	4%	0	0%	4%	5
149	6%	17	1%	5%	5	437	18%	52	2%	16%	4	247	10%	63	3%	8%	4	8	0%	0	0%	0%	4	31	1%	0	0%	1%	4
254	3%	6.2	0%	3%	6	1078	12%	1121	13%	0%	8	1291	15%	1124	13%	2%	8	9	0%	160	2%	-2%	5	12	0%	0	0%	0%	5
54	2%	0	0%	2%	4	377	11%	794	23%	-12%	7	98	3%	2493	72%	-69%	7	9	0%	5	0%	0%	4	11	0%	0	0%	0%	4
23	0%	0	0%	0%	9	1145	18%	71	1%	16%	13	1478	23%	559	9%	14%	13	11	0%	0	0%	0%	8	0	0%	0	0%	0%	8
0	0%	60.2	1%	-1%	7	543	9%	1742	28%	-20%	5	372	6%	1539	25%	-19%	5	0	0%	0	0%	0%	7	0	0%	0	0%	0%	7
3	0%	0	0%	0%	6	829	17%	46	1%	16%	7	767	16%	64	1%	15%	7	27	1%	2	0%	1%	5	15	0%	0	0%	0%	5
538	6%	0	0%	6%	5	1356	14%	359	4%	11%	8	1722	18%	297	3%	15%	8	9	0%	0	0%	0%	4	51	1%	0	0%	1%	4
520	13%	0	0%	13%	5	685	17%	223	5%	11%	6	442	11%	124	3%	8%	6	42	1%	1	0%	1%	4	3	0%	0	0%	0%	4
75	1%	0	0%	1%	5	948	16%	227	4%	12%	8	1375	23%	172	3%	20%	8	35	1%	19	0%	0%	5	2	0%	0	0%	0%	5
47	1%	165.8	3%	-2%	6	143	2%	544	9%	-7%	6	615	11%	128	2%	8%	6	5	0%	0	0%	0%	4	9	0%	0	0%	0%	4
264	14%	179.7	10%	4%	4	309	16%	163	9%	8%	5	401	21%	135	7%	14%	5	2	0%	0	0%	0%	3	9	0%	3	0%	0%	3
94	2%	0	0%	2%	4	545	11%	241	5%	6%	4	1698	33%	301	6%	27%	4	22	0%	3	0%	0%	5	72	1%	100	2%	-1%	5
585	2%	182	1%	1%	11	3948	13%	649	2%	11%	10	7776	25%	613	2%	23%	10	5	0%	0	0%	0%	7	19	0%	33	0%	0%	7
337	7%	0	0%	7%	4	791	17%	280	6%	11%	4	721	15%	387	8%	7%	4	7	0%	72	2%	-1%	5	7	0%	0	0%	0%	5
85	1%	0	0%	1%	8	3295	22%	660	4%	17%	12	2995	20%	320	2%	18%	12	12	0%	0	0%	0%	7	5	0%	0	0%	0%	7
298	20%	2.2	0%	20%	4	409	27%	302	20%	7%	4	278	18%	154	10%	8%	4	14	1%	0	0%	1%	4	14	1%	18	1%	0%	4
136	1%	0	0%	1%	7	3101	29%	424	4%	25%	10	639	6%	355	3%	3%	10	4	0%	0	0%	0%	7	15	0%	112	1%	-1%	7
440	4%	23.9	0%	4%	9	2117	20%	406	4%	16%	8	1608	15%	764	7%	8%	8	0	0%	0	0%	0%	5	5	0%	7	0%	0%	5
265	15%	9.3	1%	14%	5	256	14%	21	1%	13%	4	163	9%	11	1%	8%	4	2	0%	0	0%	0%	4	3	0%	2	0%	0%	4
72	1%	0	0%	1%	7	2034	19%	111	1%	18%	10	2023	19%	157	1%	18%	10	17	0%	0	0%	0%	7	43	0%	0	0%	0%	7
93	4%	76.1	3%	1%	5	120	5%	205	8%	-3%	4	470	18%	25	1%	17%	4	56	2%	0	0%	2%	5	6	0%	0	0%	0%	5
227	2%	0	0%	2%	6	2652	22%	497	4%	18%	9	2349	19%	313	3%	17%	9	56	0%	0	0%	0%	5	29	0%	0	0%	0%	5
294	2%	0	0%	2%	11	3315	18%	583	3%	15%	10	4291	24%	567	3%	20%	10	32	0%	0	0%	0%	8	0	0%	0	0%	0%	8
166	5%	105.2	3%	2%	5	404	11%	65	2%	9%	6	320	9%	293	8%	1%	6	10	0%	0	0%	0%	3	0	0%	0	0%	0%	3
253	4%	0	0%	4%	6	1120	19%	74	1%	18%	7	971	16%	80	1%	15%	7	3	0%	0	0%	0%	5	29	0%	2	0%	0%	5
69	1%	0	0%	1%	5	954	17%	313	5%	11%	7	298	5%	506	9%	-4%	7	34	1%	118	2%	-1%	5	21	0%	0	0%	0%	5
140	1%	0	0%	1%	6	2121	21%	290	3%	18%	8	2275	22%	375	4%	19%	8	4	0%	0	0%	0%	7	0	0%	0	0%	0%	7
86	1%	0	0%	1%	7	4380	28%	213	1%	26%	10	2485	16%	688	4%	11%	10	16	0%	0	0%	0%	5	1	0%	0	0%	0%	5
184	2%	12.9	0%	2%	7	1432	16%	178	2%	14%	6	1208	14%	377	4%	9%	6	21	0%	0	0%	0%	5	0	0%	0	0%	0%	5
269	6%	0	0%	6%	4	921	20%	427	9%	11%	4	1377	29%	256	5%	24%	4	30	1%	22	0%	0%	5	1	0%	0	0%	0%	5
6	1%	130.1	13%	-12%	3	26	3%	153	15%	-12%	4	171	17%	63	6%	11%	4	37	4%	21	2%	2%	3	1	0%	19	2%	-2%	3
647	8%	0	0%	8%	7	1526	19%	148	2%	17%	8	1347	17%	535	7%	10%	8	120	1%	2	0%	1%	6	361	4%	0	0%	4%	6
67	2%	0	0%	2%	4	568	17%	104	3%	14%	7	465	14%	164	5%	9%	7	2	0%	0	0%	0%	4	5	0%	0	0%	0%	4
386	3%	0	0%	3%	8	4258	29%	998	7%	22%	10	2969	20%	561	4%	16%	10	55	0%	0	0%	0%	7	1	0%	0	0%	0%	7
246	3%	0	0%	3%	5	921	13%	427	6%	7%	4	1377	19%	256	4%	16%	4	30	0%	22	0%	0%	6	1	0%	0	0%	0%	6
273	1%	0	0%	1%	8	2453	12%	1003	5%	7%	9	3940	19%	1017	5%	14%	9	2	0%	16	0%	0%	5	1	0%	0	0%	0%	5
7	0%	344.5	7%	-7%	5	444	9%	483	10%	-1%	7	392	8%	856	18%	-10%	7	19	0%	0	0%	0%	5	3	0%	0	0%	0%	5
304	3%	0	0%	3%	8	1603	14%	294	3%	12%	6	318	3%	896	8%	-5%	6	42	0%	13	0%	0%	9	21	0%	56	1%	0%	9
33	1%	69.1	2%	-1%	5	709	18%	137	4%	15%	5	177	5%	71	2%	3%	5	5	0%	0	0%	0%	6	29	1%	8	0%	1%	6
54	2%	86.1	3%	-1%	6	544	20%	144	5%	15%	5	400	15%	61	2%	13%	5	22	1%	5	0%	1%	4	1	0%	1	0%	0%	4
184	1%	0	0%	1%	10	3483	21%	227	1%	19%	10	1808	11%	740	4%	6%	10	60	0%	0	0%	0%	7	0	0%	0	0%	0%	7
117	4%	0	0%	4%	3	386	12%	16	1%	12%	4	185	6%	105	3%	3%	4	34	1%	38	1%	0%	4	119	4%	0	0%	4%	4
43	2%	0	0%	2%	7	342	13%	49	2%	11%	5	244	10%	262	10%	-1%	5	10	0%	0	0%	0%	4	2	0%	0	0%	0%	4
522	3%	0	0%	3%	8	5270	32%	437	3%	29%	9	2833	17%	801	5%	12%	9	7	0%	162	1%	-1%	8	51	0%	133	1%	0%	8
150	12%	162.9	13%	-1%	5	48	4%	210	17%	-13%	3	17	1%	228	19%	-17%	3	7	1%	4	0%	0%	4	0	0%	92	8%	-8%	4
175	3%	0	0%	3%	5	1542	29%	76	1%	27%	7	1037	19%	304	6%	14%	7	30	1%	0	0%	1%	5	22	0%	0	0%	0%	5
112	3%	0	0%	3%	5	1561	40%	173	4%	36%	7	406	11%	89	2%	8%	7	16	0%	0	0%	0%	4	8	0%	0	0%	0%	4
302	6%	0	0%	6%	6	391	8%	156	3%	5%	7	651	13%	68	1%	12%	7	2	0%	0	0%	0%	10	5	0%	0	0%	0%	10
521	3%	0	0%	3%	7	4869	25%	661	3%	22%	9	5235	27%	350	2%	25%	9	37	0%	15	0%	0%	5	36	0%	0	0%	0%	5
198	2%	0	0%	2%	7	5518	52%	232	2%	50%	8	684	6%	276	3%	4%	8	45	0%	34	0%	0%	6	118	1%	5	0%	1%	6
579	6%	0	0%	6%	7	470	5%	199	2%	3%	7	4698	49%	125	1%	48%	7	43	0%	0	0%	0%	6	24	0%	0	0%	0%	6
0	0%	84	0%	0%	9	2010	11%	1039	6%	5%	12	3038	16%	819	4%	12%	12	31	0%	0	0%	0%	6	22	0%	0	0%	0%	6
81	7%	0	0%	7%	4	558	45%	1	0%	45%	5	258	21%	13	1%	20%	5	3	0%	0	0%	0%	5	1	0%	0	0%	0%	5
411	5%	0	0%	5%	7	1286	15%	536	6%	9%	10	1999	24%	724	9%	15%	10	2	0%	0	0%	0%	5	2	0%	0	0%	0%	5
84	0%	0	0%	0%	8	3015	16%	774	4%	12%	12	2517	13%	351	2%	11%	12	35	0%	0	0%	0%	7	2	0%	0	0%	0%	7
293	31%	4	0%	30%	5		0%		0%	0%	3		0%		0%	0%	3		0%		0%	0%	2		0%		0%	0%	2

Appendix C: Reef Horizons Data

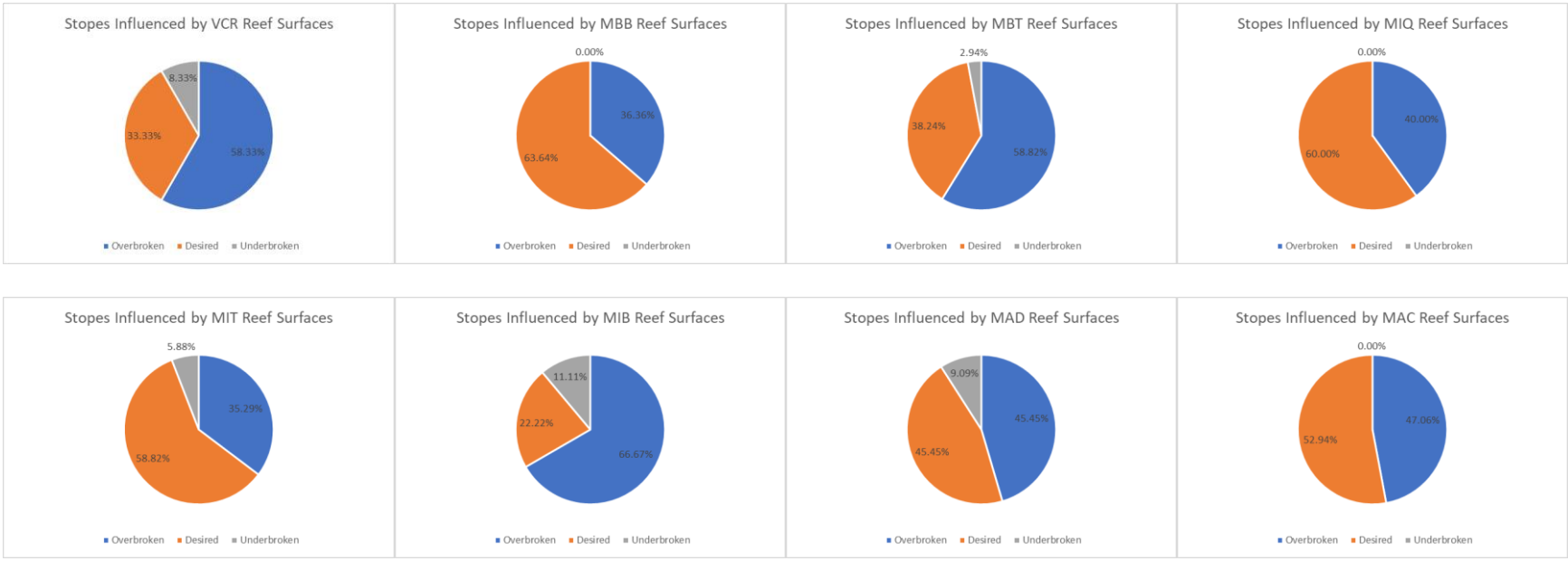
Recon Date	Reef Surface Block	Stope Name	Dimension Factor %	Stope Type	Stope Above (DC, CV, LV, OS, OD, SL)	Reef Contact Package(s)
Jan-18	2D	100 4W CUT2 LH04A	7.94%	SEC	DC	MBT, VCR, ECMC, MBB
Feb-18	2C	95 2W MP7 LHS1E	30.67%	PRI	DC	MBB, MIB, MIQ
Feb-18	1A	87 1W BW LH11	-7.20%	PRI	CV	N/A
Jun-18	2D	100 4W CUT3 LH10A	20.01%	PRI	LV	ECB, VCR, MIT
Jun-18	1C	095 1W CUT3 LHS 09B	2.67%	SEC	SL	MBB
Jun-18	1C	090 1W CUT02 LHS 5A	34.97%	PRI	DC	MIT, MIB, MBT
Jun-18	1A	87 1W B18 LHS03	-78.95%	PRI	CV	N/A
Jun-18	2D	90 3W LHS09	56.92%	PRI	CV	ECBA, ECMC, ED,MAC
Sep-18	2E	100 4W CUT3 LH07 MB	-39.61%	PRI	LV	MAD, MBT, MIT, VCR
Sep-18	1DEF	100 1BW CUT3 LHS03B	41.73%	SEC	DC	MBT
Sep-18	1A	87 1W B04 LHS08	43.00%	PRI	CV	ED, MAC, MAD
Feb-19	2E	100 4W CUT3 LHS04C	45.18%	SEC	DC	MAC, MAD, MBT, VCR
Apr-19	1C	90 1W Cut2 LH 7A	40.85%	PRI	DC	MIB, MBT
Jun-19	1C	095 1W CUT3 LHS06B	-0.34%	PRI	SL	MBB
Jan-20	2D	095 02W MPR08 LHS 04W	26.77%	SEC	LV	MAD,MBB, MIT, VCR
Jan-20	2C	95 2W MP04 LHS 03W	40.24%	PRI	CV	ECBA, ECB, ECMC
Feb-20	2G	100 2AW CUT3 LPIL 8 N	30.11%	PRI	LV	MBT
Feb-20	1C	90 1BW CUT2 LHS 04W	23.45%	SEQ	DC	MAD, MIQ
Mar-20	2G	100 2BW CUT03 LHP 01W	36.92%	PRI	DC	MBT, VCR, MIQ
Mar-20	2C	095 02W MPR04 LHS 01N	28.42%	PRI	OS	ECBAQ, ECBA, ECMQ, ED, ECT, ECBQ
Mar-20	1DEF	100 1BW CUT3 LHS 1A	49.62%	SEC	DC	MBT
Mar-20	2D	95 3W MPR07 LPIL 11S	28.59%	PRI	LV	ED, MAC, MBB, VCR
Apr-20	2E	100 4W CUT2 LHS 05E	32.46%	PRI	DC	ED, MBB, MIB
May-20	2D	90 3W CUT2 LHP 11E	71.73%	SEC	CV	ECBA, MAC, ED, ECMC
May-20	2D	100 4W CUT1 LHP 02E	16.58%	SEC	SL	MBB, MBT
May-20	1C	90 1W CUT2 LHS 06W	33.30%	SEC	DC	MBB, MBT,MIB
Jun-20	2D	100 04W CUT02 LHP 08N	32.06%	PRI	OS	ECB, MAD
Jun-20	1DEF	100 1BW CUT3 LHQ 05W	11.83%	SEC	SL	MBT, MIQ, MIT
Aug-20	1C	90 1W CUT2 LHS 08W	47.70%	SEC	DC	MBT, MIT
Aug-20	2E	100 4W CUT4 LHQ 06E	7.67%	SEQ	DC	MAC, ED, ECMC, ECB
Aug-20	1C	95 1W CUT3 LHS 07B	36.98%	SEC	LV	MIT, MBT
Aug-20	2D	95 3W CUT05 LHP 01W	37.49%	PRI	DC	ED, MAC, MAD, MBT, VCR
Sep-20	1DEF	100 1BW CUT03 LHQS 06E	25.74%	SEQ	DC	MIT, MBT, MBB
Nov-20	2D	95 3W CUT05 LPIL 01W	39.61%	SEC	LV	ED, MAC, MAD, MBT, VCR
Jan-21	2F	100 3W CUT03 LHS 04W	-14.15%	PRI	SL	ED, MAC, MIB
Feb-21	2E	100 4W CUT03 LPIL 01N-C	35.57%	SEC	LV	ECMC, VCR, MIT, MBT, ED
Mar-21	2D	100 4W CUT02 LHQ 07E	24.94%	SEQ	DC	MBB, ECB, ECMC
Mar-21	2D	100 4W CUT01 LHQS 01E	35.72%	SEQ	LV	MBB, MBT, VCR
Apr-21	2E	95 2W CUT01 LHQS 03W	26.11%	SEQ	OS	MAD, MBT, MIQ, MIT,
Apr-21	1C	95 1W CUT03 LHQ 07N	22.12%	PRI	SL	MBB, MBT, MIT
May-21	2F	100 3W CUT03 LHQ 03E	-17.11%	SEQ	LV	MIQ
May-21	2E	100 4W CUT04 LHS 05E	9.22%	SEC	OD	ECT,MAC
May-21	2F	100 3W CUT03 LHS 01E	17.16%	SEC	DC	ED, MAC,MAD, MBT, MIQ, MIT
May-21	2D	95 3W CUT05 LPIL 03W	26.92%	SEC	LV	ECT, MAC, MBB, ECMC
Jun-21	1DEF	100 1BW CUT03 LHQ 03W	27.01%	SEQ	DC	MBT
Jun-21	2F	100 3W CUT03 LHQ 03W	21.89%	SEQ	OD	ECMQ, ED, MAD, MIT
Jul-21	2E	95 2W CUT03 LHS 01S	12.90%	SEQ	SL	MBT
Jul-21	1C	95 1W CUT04 LHS 07B	37.90%	PRI	OD	VCR, MBB, MBT
Aug-21	1C	90 1W CUT01 LHS 07E	-39.23%	PRI	SL	MIB
Sep-21	2C	95 2W CUT07 LHS 01E	36.09%	SEC	LV	MBT, MIQ
Sep-21	2D	100 4W CUT03 LHQ 05W	38.11%	SEC	DC	MAC, MBB,MBT
Sep-21	2G	100 2AW CUT04 LHQ 01E	22.98%	PRI	OD	MAC, MBB, MBT, MIQ
Oct-21	2G	100 2AW CUT03 LHS 01E	35.21%	SEQ	SL	MBT, MIQ
Oct-21	1C	95 1W CUT04 LHS 07N	31.05%	SEQ	DC	MIT, MBT
Oct-21	2D	95 3W CUT03 LPIL 05W	31.86%	PRI	OD	MBB, ECMC, ED, MAC
Oct-21	2C	95 2W CUT08 LHSS 05N	17.04%	SEC	SL	MAC,MIT,MBB
Nov-21	1C	90 1W CUT02 LHS 04B	37.26%	PRI	DC	MIB, MBT, MIT
Nov-21	1C	95 1W CUT03 LHS 10B	29.17%	SEQ	SL	MBB, MBT
Dec-21	2E	100 4W CUT04 LHQS 10E	57.49%	SEQ	DC	MBB, ECB
Dec-21	1DEF	100 1BW CUT04 LHS 07W	23.74%	PRI	OD	MBT, MIT

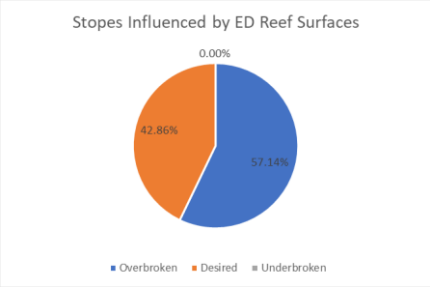
Appendix D: Individual Influence of Reef Horizons on Stopes

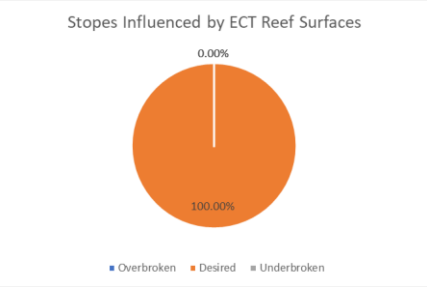


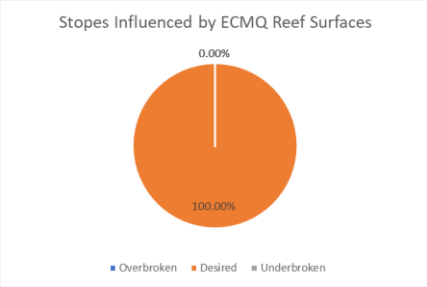

Stopes Influenced by ED
Underbreak/Overbreak
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-10.00%
-20.00%
Reconciled Stopes
Stopes Influenced by ECT
Underbreak/Overbreak
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECMQ
Underbreak/Overbreak
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECMC
Underbreak/Overbreak
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECB
Underbreak/Overbreak
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECBAQ
Underbreak/Overbreak
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECBA
Underbreak/Overbreak
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes
Stopes Influenced by ECBQ
Underbreak/Overbreak
30.00%
20.00%
10.00%
0.00%
Reconciled Stopes

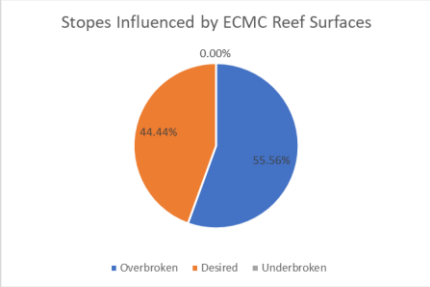
Appendix E: Stope Performance based on Reef Horizons

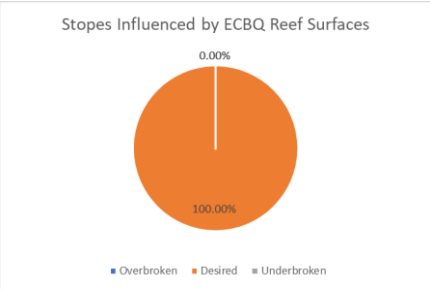


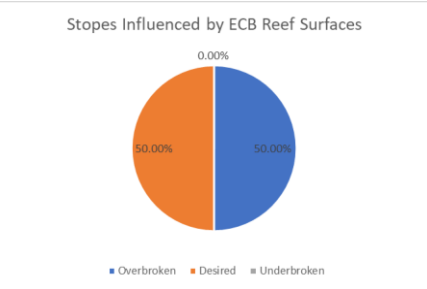

Stopes Influenced by ED Reef Surfaces
0.00%
42.86%
57.14%
Overbroken
Desired
Underbroken

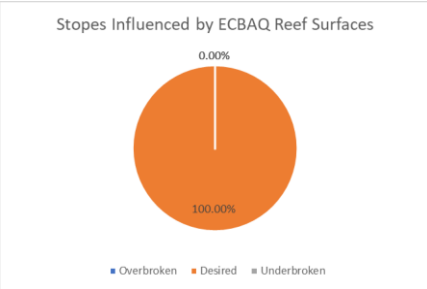

Stopes Influenced by ECT Reef Surfaces
0.00%
100.00%
Overbroken
Desired
Underbroken

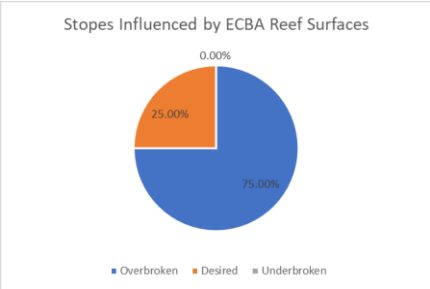

Stopes Influenced by ECMQ Reef Surfaces
0.00%
100.00%
Overbroken
Desired
Underbroken


Stopes Influenced by ECMC Reef Surfaces
0.00%
44.44%
55.56%
Overbroken
Desired
Underbroken


Stopes Influenced by ECBQ Reef Surfaces
0.00%
100.00%
Overbroken
Desired
Underbroken


Stopes Influenced by ECB Reef Surfaces
0.00%
50.00%
50.00%
Overbroken
Desired
Underbroken


Stopes Influenced by ECBAQ Reef Surfaces
0.00%
100.00%
Overbroken
Desired
Underbroken


Stopes Influenced by ECBA Reef Surfaces
0.00%
25.00%
75.00%
Overbroken
Desired
Underbroken

Appendix F: Multi-variate Model

Crown HR OLS Regression Results

Dep. Variable:	y	R-squared:	0.984
Model:	OLS	Adj. R-squared:	0.983
Method:	Least Squares	F-statistic:	655.1
Date:	Sun, 06 Nov 2022	Prob (F-statistic):	2.43e-46
Time:	18:44:46	Log-Likelihood:	3.4288
No. Observations:	59	AIC:	5.142
Df Residuals:	53	BIC:	17.61
Df Model:	5		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	-0.1476	0.172	-0.857	0.395	-0.493	0.198
Length (m)	4.0898	0.177	23.110	0.000	3.735	4.445
Width (m)	8.4070	0.253	33.200	0.000	7.899	8.915
Height (m)	0.1845	0.230	0.801	0.427	-0.278	0.646
Crown Over-break (%)	-0.1860	0.180	-1.034	0.306	-0.547	0.175
Crown Under-break (%)	0.2603	0.166	1.568	0.123	-0.073	0.593

Omnibus:	6.785	Durbin-Watson:	2.588
Prob(Omnibus):	0.034	Jarque-Bera (JB):	6.860
Skew:	-0.832	Prob(JB):	0.0324
Kurtosis:	2.858	Cond. No.	12.2

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

HW HR OLS Regression Results

Dep. Variable:	y	R-squared:	0.878
Model:	OLS	Adj. R-squared:	0.866
Method:	Least Squares	F-statistic:	76.13
Date:	Sun, 06 Nov 2022	Prob (F-statistic):	5.87e-23
Time:	18:44:46	Log-Likelihood:	-74.148
No. Observations:	59	AIC:	160.3
Df Residuals:	53	BIC:	172.8
Df Model:	5		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	-0.5618	0.611	-0.920	0.362	-1.787	0.663
Length (m)	7.0301	0.648	10.853	0.000	5.731	8.329
Width (m)	0.7489	0.949	0.790	0.433	-1.154	2.652
Height (m)	7.9984	0.807	9.915	0.000	6.380	9.617
HW Over-break (%)	1.0832	0.666	1.626	0.110	-0.253	2.419
HW Under-break (%)	-0.1814	0.647	-0.281	0.780	-1.479	1.116

Omnibus:	14.145	Durbin-Watson:	1.792
Prob(Omnibus):	0.001	Jarque-Bera (JB):	15.383
Skew:	-1.116	Prob(JB):	0.000457
Kurtosis:	4.131	Cond. No.	12.6

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

FW HR OLS Regression Results

Dep. Variable:	y	R-squared:	0.873
Model:	OLS	Adj. R-squared:	0.861
Method:	Least Squares	F-statistic:	72.60

Date:	Sun, 06 Nov 2022	Prob (F-statistic):	1.75e-22
Time:	18:44:46	Log-Likelihood:	-75.374
No. Observations:	59	AIC:	162.7
Df Residuals:	53	BIC:	175.2
Df Model:	5		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	-0.6444	0.569	-1.132	0.263	-1.786	0.497
Length (m)	6.7995	0.655	10.378	0.000	5.485	8.114
Width (m)	1.0894	0.963	1.131	0.263	-0.843	3.022
Height (m)	8.1955	0.804	10.190	0.000	6.582	9.809
FW Over-break (%)	0.5626	0.770	0.731	0.468	-0.981	2.107
FW Under-break (%)	0.5445	0.923	0.590	0.558	-1.307	2.396

Omnibus:	18.270	Durbin-Watson:	1.911
Prob(Omnibus):	0.000	Jarque-Bera (JB):	22.530
Skew:	-1.288	Prob(JB):	1.28e-05
Kurtosis:	4.591	Cond. No.	13.2

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

SDA HR OLS Regression Results

Dep. Variable:	y	R-squared:	0.786
Model:	OLS	Adj. R-squared:	0.766
Method:	Least Squares	F-statistic:	38.90
Date:	Sun, 06 Nov 2022	Prob (F-statistic):	1.42e-16
Time:	18:44:46	Log-Likelihood:	-59.025
No. Observations:	59	AIC:	130.1
Df Residuals:	53	BIC:	142.5

```
Df Model:                           5
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const          0.5396      0.443      1.219      0.228      -0.349       1.428
Length (m)    -0.4921      0.517     -0.951      0.346      -1.530       0.546
Width (m)      4.7091      0.720      6.545      0.000       3.266       6.152
Height (m)     4.8722      0.617      7.894      0.000       3.634       6.110
SDA Over-break (%)    -0.1080      0.648     -0.167      0.868      -1.408       1.193
SDA Under-break (%)    0.3029      0.615      0.493      0.624      -0.931       1.536
==============================================================================
Omnibus:                       45.768   Durbin-Watson:                   1.773
Prob(Omnibus):                  0.000   Jarque-Bera (JB):              145.440
Skew:                           2.342   Prob(JB):                     2.62e-32
Kurtosis:                       9.102   Cond. No.                         11.9
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
SDB HR                            OLS Regression Results
==============================================================================
Dep. Variable:                      y   R-squared:                       0.787
Model:                            OLS   Adj. R-squared:                  0.767
Method:                 Least Squares   F-statistic:                     39.11
Date:                Sun, 06 Nov 2022   Prob (F-statistic):           1.28e-16
Time:                        18:44:46   Log-Likelihood:                -58.902
No. Observations:                  59   AIC:                             129.8
Df Residuals:                      53   BIC:                             142.3
Df Model:                           5
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
```

const	0.4572	0.407	1.124	0.266	-0.359	1.273
Length (m)	-0.4635	0.514	-0.901	0.371	-1.495	0.568
Width (m)	4.7133	0.715	6.593	0.000	3.279	6.147
Height (m)	4.9648	0.619	8.026	0.000	3.724	6.206
SDB Over-break (%)	0.0958	0.482	0.199	0.843	-0.871	1.063
SDB Under-break (%)	0.4610	0.677	0.680	0.499	-0.898	1.820

Omnibus:	45.846	Durbin-Watson:	1.738
Prob(Omnibus):	0.000	Jarque-Bera (JB):	144.592
Skew:	2.353	Prob(JB):	4.00e-32
Kurtosis:	9.055	Cond. No.	12.0

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.