THEORY AND CRITICAL DESIGN PARAMETERS IN UNDERGROUND SLOT, WINZE, RISE OR RAISE DESIGNS

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ABSTRACT

The conventional method of underground mining involves a process known as drilling and blasting to excavate valuable ore bearing minerals through the load and haul process. Drilling and blasting processes are completed for both the development of the tunnels used to access the ore body and for mining out the ore body itself. The former being called development drilling and blasting, and the latter production drilling and blasting. In either development or production drilling and blasting, the effective recovery will be largely reliant on the extraction of the initial void created in each blast cycle. In development tunnelling, the initial void is commonly known as a Burn Cut. The initial void created in production drilling and blasting has many names such as a Slot, Winze, Rise or Raise. There are drill patterns and charge designs used to create these initial voids in the production cycle. This paper discusses common slot or winze designs for production drilling and blasting; and various critical design criteria for these. The document also aims to provide a process for completing desktop reviews of current patterns employed on sites and provides an initial guide in a process for improving the recovery of a slot, winze, rise or raise in underground mines.

SUCCESFUL INITIAL BLASTS, THE KEY TO SUCCESFUL UNDERGROUND DRILLING AND BLASTING

As underground mines operate at increasing depths to extract ore, operating costs are increasing making it pivotal for miners to operate sustainably and efficiently. Production targets must be met in a timely manner to ensure operating and capital costs are minimised and the intended return on investment is delivered. The optimum mining of an orebody in an underground open stoping operation is fundamental to productivity. Effective mining in bulk underground mining is largely reliant on the recovery of the initial void created by drilling and blasting. These initial voids are known by various names such as the long hole rise, slot, or winze of the stope. These initial blasts in stoping or caving operations can be drilled by either top hammer drilling equipment or in-the-hole drilling equipment or in some cases a combination of both. Diligent drilling and blasting of these will facilitate efficient mining of the designed open stope ensuring production of the orebody remains within mining schedules at a minimum cost. When an operation struggles in opening the initial void of a stope or a cave, it causes a negative impact on productivity, mine schedules and mineral recovery and impacts the overall economics of the mining operation. Each mine thus needs to understand the parameters that make the sites initial slot or winze blast succesful and to understand what aspects can be changed to suit newer rock conditions and site-specific constraints.

Whatever the bulk underground mining method employed, whether it be open stoping, sub level caving or block caving, the success of the initial blast is dependent on the successful extraction of the slot. Once this initial void is opened, the rest of the drilled-out rings can be charged and fired successfully. To simplify the explanation, an open stoping operation will be used to explain the process of production blasting and the term slot used for the initial void created in the stope. In a sub level open stope that uses down hole drilling and charging, a stope is drilled out using long hole drilling equipment. The stope can be split into two parts, the first being the slot (long hole rise, winze etc). This is the initial part of the stope that is mined out to create a sufficient void for the bulk of the stope to be blasted into. The remaining bulk portion of the stope usually comprises of the main production rings. Figure 1 below shows a long section of a simple downhole and uphole stope design differentiating the slot from the main rings.

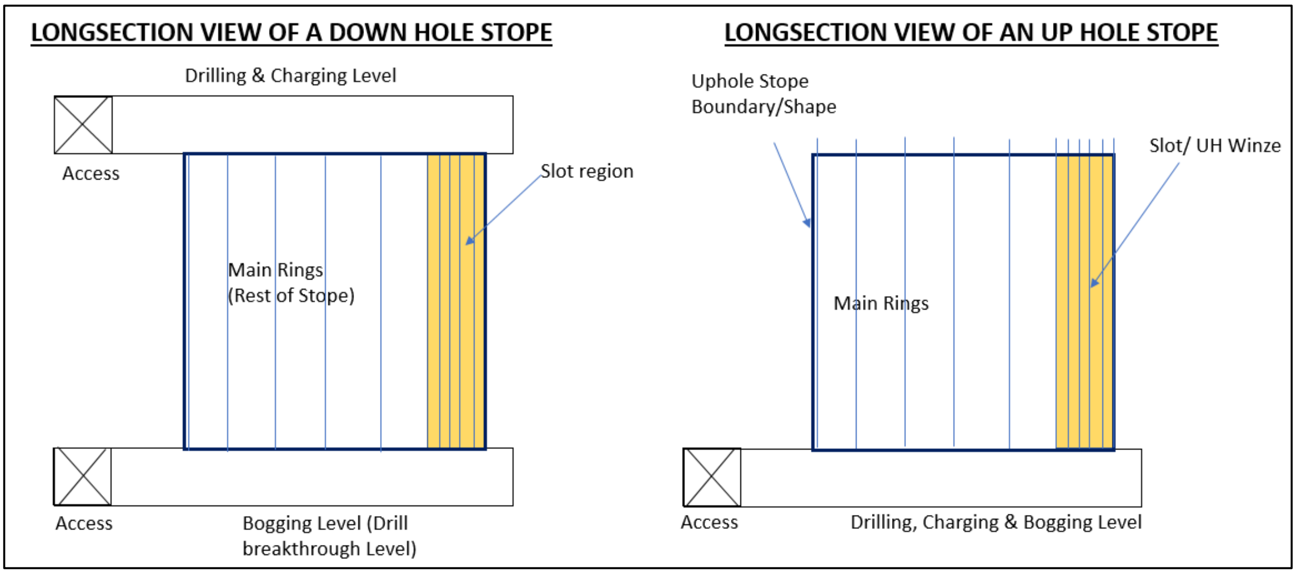


Figure 1 - Long section view of a downhole and an up hole stope showing the slot area and the main rings area of a stope

Depending on stope geometries and drilling platforms, the main rings are usually radially drilled blast holes that are charged and blasted into the void created by the slot blast. If the slot blast is unsuccessful, it is highly likely that the main ring blasts will also be unsuccessful. An unsuccessful slot blast will sometimes be referred to as a frozen or bridged slot as the material is deemed to be frozen in place or creates a bridge shape with the void and the host rock. This frozen or bridged blast will then force the mine to employ recovery drilling and charging options in an attempt to recover this frozen or bridged material. It is therefore critical, especially in up hole stopes that every effort is made to ensure these initial blasts are successful. It is very difficult and, in some cases impractical, to recover a frozen or bridged up hole slot blast. This can result in ore sterilisation that not only affects the mine production and ore recovery, but also delays the mining cycle.

CRITICAL DESIGN PARAMETERS IN SLOT DESIGNS

Slot, Long hole rise, winze definition

The mining industry over the years has seen many different design standards for slot, winze, long hole rise or raise designs that have become widely accepted in many mine sites. The slot or long hole rise is characterised by a series of drilled out holes in a small area of the stope. This area is usually in a 3mW x 3mL or 4mW x 4mL box with varying hole lengths depending on stope shape. Other dimensions are also used in the industry but to a lesser degree. One set of drill holes in the slot box would have a smaller diameter hole that will be charged with explosives. The second set of drill holes will have a larger diameter hole and will remain uncharged. These larger diameter uncharged holes are commonly referred to as reamer holes or relief holes. These uncharged relief holes will act as an internal void into which the earlier firing blast holes in the sequence in the slot will blast when initiated. When the first blast hole in a blast event is initiated the material will fragment and heave into the nearest open void. In a slot blast, the open voids are the larger diameter uncharged relief holes and the drive void below or above the slot box.

In cross section of the slot design, the blast holes that will be charged are strategically located near the uncharged relief holes. The blast holes will be charged and blasted in a sequence that will allow the charged holes closest to the relief holes to fragment and heave into these larger diameter holes before falling into the drive void below. Down hole slot designs (those drilled and charged as down holes) can be mined out in multiple charge and blast events. These different events are commonly referred to as lifts. These lifts are charged and fired in a similar fashion to a vertical crater retreat blast. However larger lift heights are usually taken due to the nature of the slot design and the volume of the available drive void below and above (in final lift or cap blasts) in the charged area. In an up hole stope, a stope that is drilled and charged upwards from a single development drive, the slot is charged and fired in one blast in large open stoping. Air leg raising uses different methodology and will not be discussed in this paper.

There are several factors that determine the effectiveness of a slot design and these can be used to both assess or review existing mine designs or to help draft a new design for a new mine. These factors, if adequately addressed in the design phase, can assist in improving the success of a slot blast. These design factors include, but are not limited to:

1. Critical void ratio and overall blast void ratio;
2. Explosive energy distribution;
3. Redundancy in design;
4. Blast hole shielding;
5. Blast hole delay timing;
6. Blasthole sequencing;
7. Uncontrollable factors in drill and blast design, for example available equipment (depending on what part of the mining cycle you are in) or geological, geotechnical and hydrological conditions..

These are some of the important concepts to review when analysing a slot design. These factors will aid in ensuring a slot or winze design will be consistently successful over the life of the mine. A successful slot blast is one that creates an open avoid as per the design shape. That is the cavity scan that is taken after mining this slot closely resembles the design shape created by the drill and blast engineer. Careful consideration will need to be made regarding site geology, mining method and equipment limitations when determining a slot design. Certain uncontrollable factors like site geology or equipment limitations will also influence the slot pattern used. Equipment limitations refer to both drilling and charging equipment, for example, can the drilling equipment drill the required blast hole and reamer hole diameter at the required lengths? Can the charging equipment effectively charge these drilled holes? These factors are much like the design considerations when optimising a burn cut design for development or tunnel advance profiles. The following parameters are briefly explained in the following section. The authors have selected the most common and simplest forms of these calculations and methods to use in design reviews for the purpose of this document. Note that there are other calculations that exist as well and a more in-depth discussion is beyond the scope of this paper.

Critical Void Ratio / Void Space Ratio and Overall Blast Void Ratio

Critical Void Ratio (CVR) or Void Space Ratio (VSR) is the first important concept to analyse when reviewing a slot design as this parameter will determine if the blast hole to relief hole distance is sufficient to allow for both material swell and heave in the cut area. The CVR or VSR formula is the ratio of the sum of the area of drill holes (both charged and uncharged) versus the difference between the area of the cut and the sum of the area of the drill holes in the cut.

$$Critical\ Void\ Ratio\ (\%) = \frac{Area_{Empty\ Holes} + Area_{Blast\ Holes}}{Area_{Cut} - \left(Area_{Empty\ Holes} + Area_{Blast\ Holes}\right)} x\ 100$$

This ratio will help to clarify if the cut area has enough void for the initial blast holes in the sequence to break into.

For successful slot design’s, the shot hole must be close enough to “easily” blast into the relief holes or reamer holes and must be timed slowly enough to allow it to heave and fall into the existing void before the next blastholes in the sequence are initiated. In most areas the slot is charged with electronic detonators which provide accurate timing and assist in preventing cut offs. Good practice suggests that void ratios for cross sectional area using the above formula are above 15%, Hagan (1998). Hagan also recommends that 15 percent of the cut should be relief holes although he does not specify how much of the face is included in the cut area.

It is generally accepted in the industry that if the shot hole in a slot is too far away from a nearby void or relief hole, it struggles to move the blasted material into the relief hole area. This over confinement of the shot hole would create excessive ground vibration and likely freeze the blast. It also increases the risk of other failure mechanisms in a blast such as sympathetic detonation, dead pressing of the explosives and charge column dislocation resulting in misfires in nearby blastholes. Due to the nature of the slot design and its high drilling and charging intensity in a small area, these phenomena are common in many slot blasts. Detection of such failures have become more evident as mines introduce near field blast vibration monitoring into their stoping reconciliation process.

The authors of this document consider the area of the cut to be the area in which the blast holes immediately surround the relief holes for long hole rises. For raise bore drilled slots, the area of the cut would either be between the shot hole closest to the large diameter relief hole and the relief hole itself or the initial blastholes forming the inner box shape (or circular shape) and the relief hole. The relief holes in these raises bore designed slots range from 750mm to 1.1m in diameter and tend to be sufficiently large to provide a high critical void ratio in the cross-sectional area.

It is important not to confuse the CVR or VSR with the overall void ratio for the blast. The overall void ratio (commonly just referred to as the void ratio) is the ratio of the existing void volume versus the volume of the material to be basted.

$$Overall\ Blast\ Void\ Ratio\ (\%) = \frac{Blast\ Shape\ Volume}{Existing\ Void\ Volume} x\ 100$$

The void ratio is expressed as a percentage and also accounts for the broken ore's swell factor after blasting. The material swell factor is the increase in volume when this in situ material is blasted. An accepted rule of thumb is that if this swell factor is not known, then a conservative figure of 25-30% be used. There are several methods to calculate this void ratio however the authors preferred method is described here.

The overall void ratio will determine if the volume of material to be blasted will fit in the available or existing void. It is recommended to maintain this ratio below 90% to prevent freezing or bridging the blast. If the overall blast void ratio more than 100%, there will not be enough available void for the volume of blasted material to heave into. This will result in an over confined, frozen or bridged blast and will likely cause recovery issues when mining this design.

This calculation is a quick and easy check to assist drill and blast engineers to evaluate blast shapes after completing a drill design.

Shielding and shadowing of initial blastholes in sequence

Another critical parameter in slot or winze designs is shielding and shadowing. Shielding provides protection along a direct line of site between the first blast hole in sequence and the next blast hole in sequence. This is achieved by designing and drilling a relief hole in between these two charge holes. It is recommended to provide initial shielding from the first hole in sequence and the next charged hole as this minimises the risk of sympathetic detonation and or charge column dislocation.

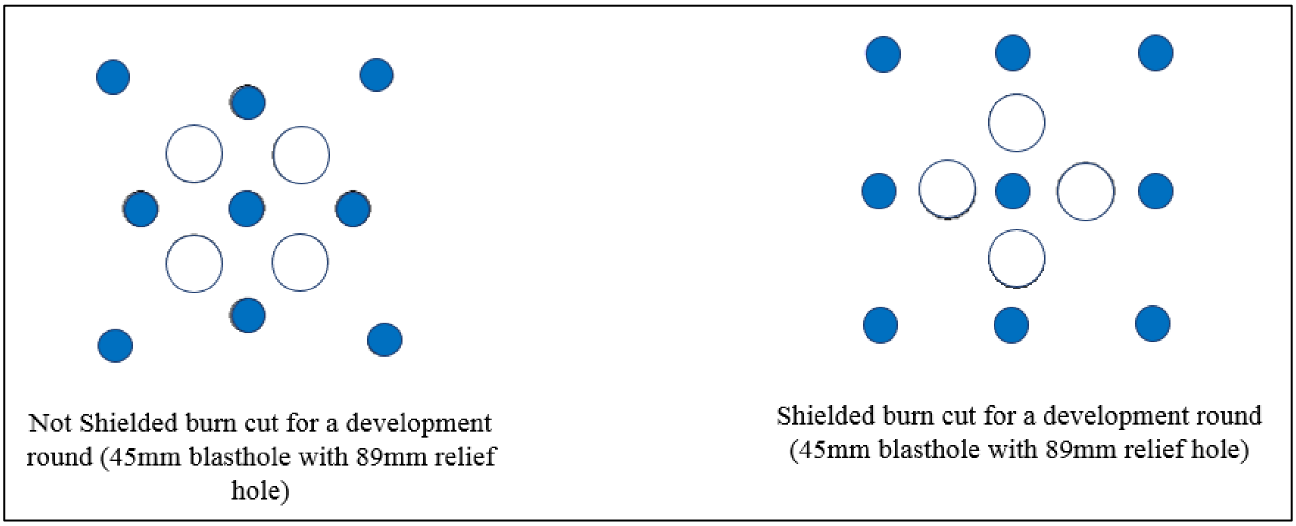


Figure 2 - Non shielded and shielded burn cut designs for a development round drilling pattern

Shielded designs provide protection for the earlier firing blast holes in the sequence, refer Figure 2. Should there be an issue or concern with out of sequencing blasting from these inner cut blast holes, a shielded design could be an option to alleviate or minimise this risk. Structures encountered during drilling could also cause blastholes to interact out of sequence and thus the slot area should be adjusted if the area is highly structured.

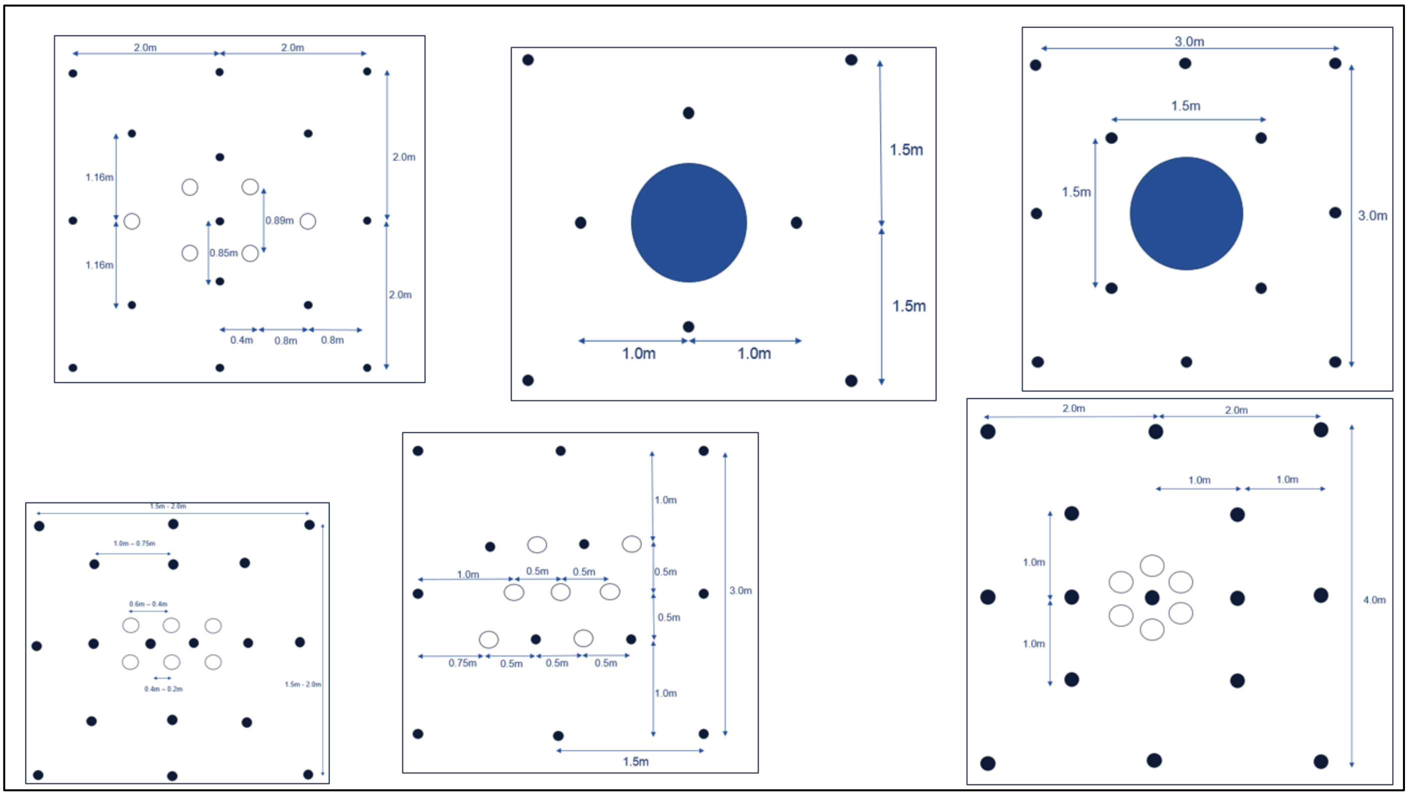


Figure 3 - Various frequently used underground slot designs

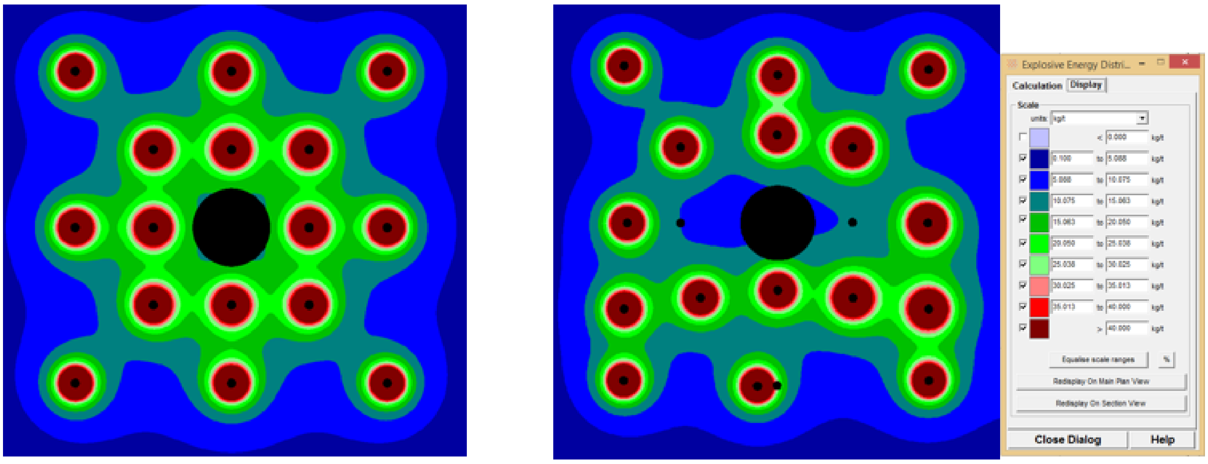
Powder Factors & Energy Distribution Models

Powder factors and explosive energy distribution models are a good indicator of the total mass of explosives used per unit volume or mass. Powder Factors are a ratio of the average weight of the explosive used per unit weight of rock (or volume of rock) whereas Explosive Energy Distribution Models are a simple means of showing how the powder factor varies across an underground blast design. This provides an indication of whether a site is overcharging or undercharging these respective blast patterns.

The use of powder factors in the underground drilling and blasting process is a quick first check in the process however it does not factor in constraints in the underground environment, including but not limited to drilling and bogging horizons, different blast types (slot or long hole rises, development blasts, main rings blasts etc). A better approach would be to analyse a design from an explosive energy distribution model or from an individual blast hole damage radius aspect. Simulating 2D or 3D explosive energy distribution models would show designers a visual indication of energy being distributed both within a ring and between rings. This is critical in identifying areas where there is a larger or smaller than ideal energy distribution.

In an ideal scenario, the blast holes in a ring are spaced out such that adjacent blast holes undertake the same amount of work in both fragmenting and heaving blasted material into the existing void. Both must be spaced out far enough to provide sufficient area of influence in a volume of rock and close enough to provide hole-to-hole interaction. In most underground drilling horizons, the drill hole collars are closely spaced together and in such instances, it is best to stagger the uncharged collar. Using Energy Distribution Models, design engineers can optimise this uncharged collar and therefore reduce the risk of sympathetic detonation from nearby charged holes.

Explosive Energy Distribution Simulation (EED) completed in JK Sim Blast for 3m x 3m slot box with a 760mm Rhino drilled relief hole. 102mm blast holes charged with 0.91g/cc emulsion for a blind up hole. Drill holes surveys and mud maps were used to simulate a more realistic EED model.



EED completed for drill design.

EED completed for actual hole surveys. In this situation, several hole were left uncharged. Blast Hole timing and sequencing adjusted to match actual survey data.

Figure 4 - Explosive Energy Distribution for drill design vs actual hole location

As shown in figure 4, deviation of drill holes within the slot can create a uneven and sub optimal explosive energy distribution. Some holes may be overburdened and for others the high explosive energy distribution could increase the risk of sympathetic detonation, column dislocations or explosive product de-sensitisation. Such a result will become apparent when near field blast vibration monitoring data is analysed.

Slot blast hole design timing and sequencing

It is vital for timing within the slot blast to be relatively slow compared to the main production ring blasts. This is to allow for effective clearing of broken material before the next holes in the sequence are initiated to help minimise material freezing or bridging within the shot. This timing will depend on the length of the slot and the inclination of the slot design. A general rule of thumb is to use a timing range from 20 – 60 milliseconds per metre of charge column in the blast hole. This range can be varied to allow for different inclinations of the rise and site-specific constraints such as relief hole diameters, slot design pattern, geology of the host rock and historical performance of slot designs on site. The earlier firing blast holes in the slot design should be the slowest in the blast and later firing blast holes can be sped up. This means that once the inner box of the slot pattern has been cleared, the remaining blastholes in the outer box can be sped up to a quicker timing range than the rule used for the inner box. For example, a mine might use 40 milliseconds per metre of charge in the inner box for the first 5 blastholes. Once these 5 blast holes have been initiated, the design timing is sped up to 25 milliseconds per metre of charge. This is acceptable as it is still within the industry rule of thumb and it is not uncommon in many underground mines to use this sort of delay timing rule within the slot region of a stope.

Blasthole delay timing of slot patterns varies from site to site and careful Quality Assurance and Quality Control monitoring ought to be undertaken should a site wish to change or alter an existing set of timing parameters. In addition to standard site post blast reconciliation processes, best practice monitoring would also include near field blast vibration monitoring to clearly identify if holes in the pattern are performing to expectation.

In an ideal blast hole firing sequence, whether for a slot blast or a ring blast, the blast holes that have the best breakout angles should be the first to fire, that is, those that are closer to the free face or void. In a slot blast, the shot hole or the first blast hole in the sequence will be the one that is closest to the relief holes. The next blast holes in the sequence should fire into the newly created void and subsequent blast holes will follow this theory opening the void to a point where the initial slot box has been fully opened. This type of sequencing will optimise the actual drilling underground. In areas where in hole surveys are not completed to measure actual drilling, mud maps or stringing of holes can be used to identify which blast holes are closer to the relief holes. Should excessive drill hole deviation occur or be a concern on site, drilling of another shot hole might be required. Although this does push out stoping schedules, it will give the slot blast the best chance of success and in most instances be less detrimental than a frozen / bridged blast.

Uncontrollable and controllable factors in drill and blast design

Slot designs, like production ring designs, have certain controllable and uncontrollable variables that influence the design. Uncontrollable variables include but are not limited to rock mass characteristics such as rock density, presence of geological structures, plasticity, and rock strength; as well as ground water, mining method, ore orientation and ore grade; and equipment restrictions. Controllable factors include hole diameter, hole length, pattern dimensions, drilling configuration, explosive type, confinement, stemming material, uncharged collars, initiation sequence, blasthole delay timing and blast size. Certain variables listed in both categories could exist in either category depending on what part of the mining cycle they fall. For example, if the designer is in the feasibility stage of mining, mining method, stope heights and equipment selection (equipment limitations) can be controllable factors however these generally become uncontrollable once in production.

Understanding these levers and at which point they can be pulled will aid in completing optimal site-specific drill and blast patterns. Factoring in these variables in slot designs and using the guidelines stated previously in this document, drill and blast engineers can design patterns that will have high success rates in recovery, providing repetitive and consistently positive results.

DESIGN RECONCILLIATIONS: COMPLETING THE *PLAN, DO AND REVIEW* PROCESS

Design Versus Actuals

A vital but often overlooked part of the drill and blast design and implementation process is the reconciliation process. The reconciliation process closes the loop of the *plan, do and review* cycle for mining of open stopes. It will identify what was done right, what was done wrong and helps to identify areas of improvement in the mining process. This review is vital to ensure learnings from each stope in a mine is recorded so that the information can used to tailor newer designs or help to mine newer stopes with similar traits. It will also record important performance actuals such as overall recovery and dilutions of open stoping operations.

Most mines will use mine records such as void scans, bogging reports, drilling, and charging returns (paperwork from mine operations) to review the design versus the mined-out area. Information such as dilution, underbreak, overbreak and any adverse issues encountered will be highlighted and discussed. Important drilling and blasting key performance indicators can be obtained from this including:

- Design drill and powder factors
- Drilling and charging rates
- Dilution
- Overbreak and underbreak
- Cavity scan versus design shape
- Actual equivalent linear overbreak slough (ELOS)

These parameters should be captured in the blast reconciliation process to assist drill and blast engineers, shot firers and other personnel make informed decisions regarding site specific issues in the blasting processes. This data should also form the basis for any future drill and blast optimisation project.

Near Field Blast Vibration Monitoring

With conditions being both site specific and often changing within a mine, it is highly recommended to include near field blast vibration monitoring as part of the drill and blast reconciliation process. Near field blast vibration monitoring has come a long way in the underground space with newer technologies to suit different monitoring projects. Equipment manufacturers can supply equipment to measure blast induced ground vibration in either velocity or acceleration. In near field blast vibration monitoring, the monitor is usually installed 20 – 60m away from the blast. At this distance, the vibration signals measured have a higher frequency and lower duration than those measured further away. The objective of this type of vibration monitoring is different from most far field environmental monitoring where the structural integrity of a building or infrastructure is needed to be protected. For further field monitoring, ground vibration induced by blasting is monitored near critical infrastructure to ensure that there is no permanent damage caused by the blasting process. In near field vibration monitoring, it is the blast performance that is of greater interest.

Vital information can be obtained regarding explosive product performance, blast hole detonation and blast hole interaction due to sequencing and delay timing. Blast induced ground vibration data retrieved from specialised monitors can provide a detailed review of the blast and give quantitative feedback on individual blast hole performance. Using scale distance laws and site constants, peak particle velocity or acceleration measurements can be used to determine the performance of each blast hole and compare the expected results. This, in conjunction with bogging inspections, fragmentation analysis, cavity scan results and operator return will give the drill and blast engineering team the ability to evaluate the effectiveness of the design and to compile a more in-depth stope reconciliation. It will also strengthen the site’s ability to investigate unsuccessful blasts and identify key failure mechanisms and improvement opportunities.

Near field blast vibration monitoring is critical to understanding slot blast performance. Whether reviewing an existing design or attempting to use a new design, the data from vibration monitoring studies will aid in analysing the overall blast outcome and give insights into improvement initiatives. Using historical data from site along with near field blast vibration studies, drill and blast engineers can adjust drill hole spacings and burdens, blast hole delay timing within the slot box, and blast hole sequencing to improve rise design mining.

ACHIEVING AND MAINTING KEY PERFORMANCE INDICATORS IN STOPING

The critical design parameters mentioned earlier in this document are used in many of the common slot patterns found in the underground mining industry in Australia. These patterns are usually adopted by mine engineers and experienced mining professionals from experience on previous operations or from company standards and are introduced into newer mines taking into account the controllable and uncontrollable drill and blast design factors stated earlier. These slot designs are proven and have a generally high success rate if designed and implemented correctly.

It is important to note that the slot, winze, rise or raise design selected as standard for an underground mine must show consecutive successful results. These results must be reviewed and updated to track the success rate of the initial blasts and the stope as a whole. The reconciliation methodology mentioned in the previous section is a vital part of this process.

The main requirement for the slot blast is to open an initial void for the rest of the stope or the cave to fire into. It is good practice to always complete void scans after bogging of the slot or rise blast to ensure there is sufficient void to progress with charging and firing the next rings in a blast. This is especially important in blind uphole slot blasts.

The theory and methods discussed within this document are from multiple sources, accepted industry rules of thumb and best practices and are illustrated here to assist with sharing knowledge in the critical design parameters of a slot, rise, winze or raise design. There is no *one design fits all solution* and close attention must be paid to the drill and blast design fundamentals when selecting or reviewing a slot design for a mine.

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REFERENCES

Bollinger, G. (2018). *Blast Vibration Analysis .* New York: Dover Publications Inc.
Dyno Nobel. (2020). *Explosive Engineers Guide.* Dyno Nobel Asia Pacific.
IRing Inc. (2021). *Raise Design and Operations Blasting*. Retrieved from iRing INC - Knowledgebase: http://www.iring.ca/_Knowledgebase/module_6_2_print.html
Richards, A. B., & Moore, A. J. (2005, February). Blast Vibration Course, Measurement Assessment Control. *Terrock Pty Ltd*. Eltham, Victoria, Australia: Terrock Pty Ltd.
RIVEY Associates, Inc. 2005. (2005). Tunnels, Shaft and Development Blast Designs. *Underground Blasting Technology*, 22-23.
Wargem, E. (2020, September 16). Stope and Raise Design and Timing_Final_DynoConsult_UGD&B_Workshop2020. Mt Isa, Queensland, Australia.