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Raiseboring in poor ground: consolidation and support methods

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Abstract

At Rio Tinto Kennecott's underground operation, ventilation raises and secondary egress escapeways are developed using raiseboring. Ground conditions in the underground mine are highly variable, ranging from good (Q > 10) to very poor (Q < 1.0). Following a raise failure in 2022 attributed to weak ground conditions, it became evident that vertical development would pose a challenge at Kennecott.

In response to the increased risk of instability during raiseboring, site implemented strict controls including pre-support, lining, canning, controlled raiseboring rates and most critically, ground consolidation. Ground consolidation is achieved through grout rings, comprised of vertically drilled and grouted perimeter holes around a planned raisebore diameter. Primary, secondary, and where necessary, tertiary grout rings are strategically designed to target and consolidate weak rock masses and thick fault zones.

Among the implemented controls, grout rings have proven to be highly effective in improving raise stability and stand-up time. Since adopting this methodology, 11 raises have been successfully developed in challenging ground without any stability issues. This paper presents an overview of the design methodology and execution strategies for grout rings. It outlines the overall approach to ensure successful raiseboring in challenging ground, and highlights key lessons learned to date.

Keywords: *vertical development, raisebore, ground consolidation, grout rings*

1 Kennecott Mine

Rio Tinto's Kennecott mining operation is situated 30 km southwest of Salt Lake City, Utah, USA, and comprises both open pit and underground mining operations. The open pit, commonly known as Bingham Canyon Mine, has been in operation for more than 120 years and is recognised as the deepest open pit mine in the world. The pit extends approximately 1.2 km in depth, 4 km in width, and covers an area of 7.7 km^2. The underground operation is located within the northern wall of the open pit. Whilst underground mining has been undertaken in the past at Kennecott, the most recent project resumed in 2021 with the lower commercial skarn (LCS) and north rim skarn (NRS) projects (Figure 1). The LCS and NRS orebodies are mined using the sublevel open stoping method and are located approximately ~980 m below surface.

The underground mine is hosted within high-grade copper-gold skarn mineralisation associated with the larger Bingham Canyon porphyry copper system. The LCS and NRS are both structurally complex orebodies comprised of highly altered and extensively damaged rock mass. Multiple regional fault systems intersect the mine footprint and are characterised by large shear zones comprised of rubble and weak, highly fractured rock mass. In addition, intrusive latite porphyry (LP) dykes also intersect the underground and are commonly associated with weak infill along the lithological margins. Collectively, these complex geological features create highly variable ground conditions that present geotechnical challenges in the underground.

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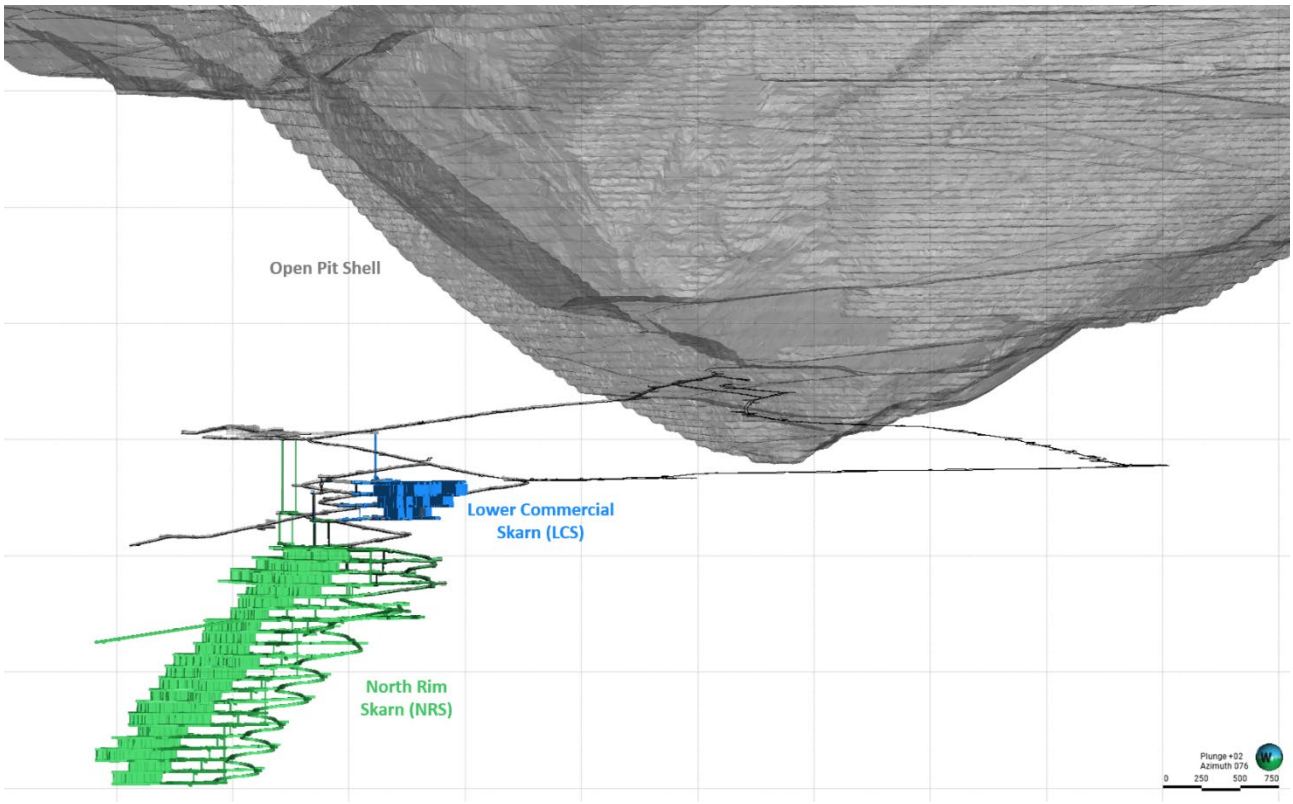


Figure 1 Conceptual layout of Rio Tinto Kennecott mine's open pit and underground operations (looking northeast, scale in feet)

2 Vertical development

Vertical development forms a critical component of the underground mining strategy at Kennecott by providing ventilation and secondary egress escapeways. To date, the site has developed 12 raises; 11 successfully and one unsuccessfully. Raise dimensions vary from 15 to 65 m in length, with diameters of 1.8 to 2.1 m for escapeways and 3.6 m for ventilation raises.

2.1 Raiseboring challenges

After underground mining resumed in 2021, the first vertical development excavation was raisebored in December 2022. The escapeway raise was designed with a length of 82 m and a diameter of 1.8 m. Prior to development, a geotechnical assessment was completed using a cover hole located approximately 7 m from the planned raise location. The assessment highlighted that the excavation would intersect a thick LP dyke lens containing weak infill. Based on the information available at the time, the risk of overbreak was considered manageable and the location of the raise was approved.

The pilot hole was drilled without issues; however, after approximately 3.5 m of reaming, the rods became stuck and the reamer head had to be lowered. Further investigation revealed that the pilot hole had collapsed, which required grouting and re-drilling before raiseboring could continue. After raiseboring was complete, excessive ravelling was reported from the bottom of the raise. A scan identified overbreak along the LP dyke structure, up to 12.8 m in some areas (Figure 2). Despite attempts to remediate the raise, it was ultimately backfilled and abandoned.

The 2022 escapeway raise failure highlighted the cost and schedule impacts associated with complex raiseboring. In response, stringent controls and operational measures were implemented to reduce the likelihood of future raise failures.

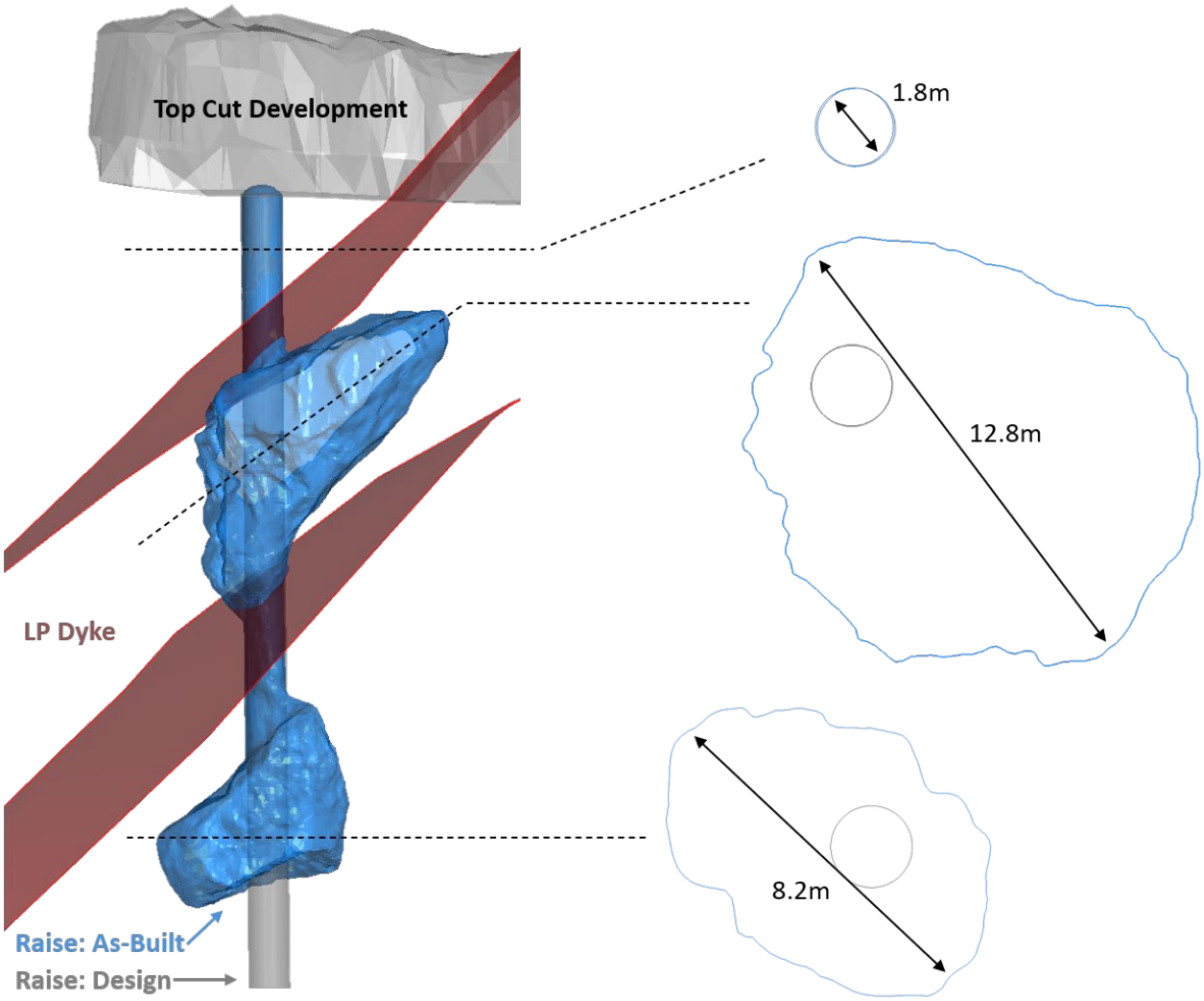


Figure 2 Cross sections of the 2022 failed escapeway raise

3 Geotechnical assessment

Comprehensive geotechnical assessments are completed for every raise developed at Kennecott. These assessments are used to determine the most suitable raise dimensions, location and the appropriate pre-support and post-support requirements. It is worth noting that, in all cases, a concerted effort is made to design raises within competent ground rather than rely on pre-support and post-support measures. However, given the highly variable rock mass at Kennecott, this is often not possible.

3.1 Cover hole

For each raise, a dedicated cover hole is drilled down the centre of the designed location. This cover hole provides raise-specific structural and geotechnical information, allowing localised ground conditions to be well understood and assessed prior to development. Due to the highly variable rock mass at Kennecott, dedicated cover holes for each raise are non-negotiable, as ground conditions can vary significantly over short distances. The effect of this type of rock mass variability is also documented by Scott et al. (2010), further supporting the requirement for cover holes to be designed within the raise footprint.

After raise cover holes are drilled, they are surveyed to confirm the hole has not deviated significantly from design. This is particularly important for long raises, where the risk of deviation increases with depth. Excessive hole deviation can result in data being collected outside the planned raise footprint.

The geotechnical assessment would then be completed using information that is not actually representative of ground conditions likely to be encountered during raiseboring.

Cover holes are structurally and geotechnically logged, with special attention paid to core recovery and core loss, discontinuities, alteration, weak or swelling infill, open joints, fault gouge, fracture frequency, microdefects and core discing. In addition to logging data, drilling crews provide feedback on penetration rate (indicates ground hardness), core loss (indicates poor ground) and drill fluid retention loss (indicates void or highly fractured ground). This information offers valuable insight into ground quality and weak zones that are not always identifiable from core alone.

3.2 Empirical assessments

Cover hole logging data is used to complete raise stability assessments. At Kennecott, the McCracken & Stacey (1989) method (M&S method) is used, which is based on the Q-system (Barton et al. 1974) with minor modifications to derive the raisebore quality index (Q_R). Raise stability is also assessed against the case history databases presented by Peck et al. (2011) and Penney et al. (2018). Figure 3 highlights that the 2022 failed raise plots within a cluster of overbroken and failed raisebore case histories. Since then, several raises have been successfully completed with additional controls, including a 20 m raise that plots within a similar region as the failed raise. The success of this raise is attributed to its shorter length, the use of grout ring consolidation and bottom cut cables, and the immediate application of spray lining post raiseboring.

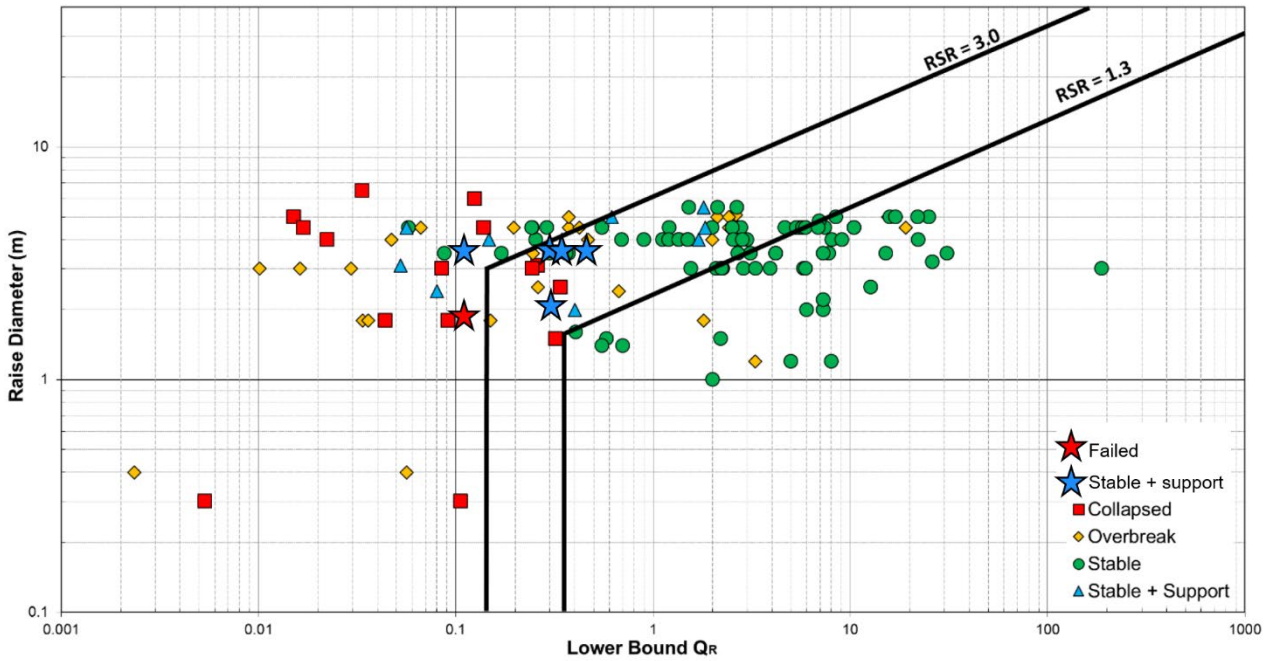


Figure 3 Kennecott raises plotted against case studies of raisebore stability, after Penney et al. (2018)

3.3 Support recommendations

Pre-support and post-support recommendations for vertical development are formulated based on cover hole logging data, empirical assessment analysis and feedback from drilling crews. Recommendations consider cost, schedule, impact to development and production activities, and operational capabilities. They also consider whether the support method will be effective. As an example, rock type and infill material need to be well understood prior to recommending pre-consolidation. Grout rings are a relatively expensive pre-support measure and should only be implemented where there is a high degree of confidence that grout migration will occur. At Kennecott, high pressure grouting has proven successful in broken, highly fractured, blocky rock mass, but has shown limited success in areas with clay rich or sandy infill. This aligns with the findings of Scott et al. (2023), who noted that both rock mass porosity and interconnected porosity are key factors controlling the effectiveness of consolidation grouting methods.

3.4 Key learnings

Gathering data for geotechnical assessments to provide pre-support and post-support recommendations has highlighted the following key learnings:

1. For every raise, a dedicated cover hole should be drilled down the centre of the designed location. In highly variable ground conditions, such as those at Kennecott, offsetting a hole by even tens of metres can intersect significantly different geotechnical conditions and may not result in an accurate geotechnical assessment.
2. Drilling crews need to record drilling information and communicate it to the geotechnical team. Information such as penetration rates, core recovery/core loss, and drill fluid retention loss can provide valuable insight into ground quality and identify weak and fractured zones.
3. Pre-support and post-support recommendations should be practical and effective. Grout rings should only be recommended where drillcore and geotechnical assessments indicate that the ground conditions are amenable to consolidation, as ultrafine grout is generally ineffective in clay rich or sandy infill.

4 Pre-support methods

Vertical development geotechnical assessments highlight the requirement for pre-support measures to be installed prior to raiseboring. At Kennecott, 2 pre-support methods have been successfully implemented: pre-consolidation through grout rings and bottom cut cable bolts.

4.1 Grout rings

As previously noted, raises are designed to avoid poor ground conditions wherever possible; however, it is not always achievable due to the structural complexity of the orebody and the variability of ground conditions. As a result, pre-consolidation has been adopted as a standard pre-support method for raises designed in poor or challenging ground.

Pre-consolidation is achieved through grout rings, also known as grout curtains or pre-grouting. Holes are drilled around the perimeter of a planned raise diameter and pressure grouted using ultrafine grout. The objective of the grout ring is to improve the overall competency, cohesion, and strength of the rock mass, thereby reducing the likelihood of instability during and immediately following raiseboring.

4.1.1 Hole spacing

Grout rings are drilled using a primary, secondary and tertiary sequence (Figure 4). Primary and secondary holes are drilled as standard practice, while tertiary holes are only recommended where additional reinforcement is required near the raise collar. Holes are drilled and grouted sequentially, for example, hole #1 is drilled and grouted before moving to hole #2, and so forth. Although it may seem more efficient to drill all primary holes prior to grouting, it increases the risk of unintentionally grouting adjacent open holes. This can lead to unplanned re-drilling and associated cost and schedule overruns. Furthermore, grout loss into adjacent open holes can prevent target grouting pressures from being achieved, reducing grout penetration into the surrounding rock mass and reducing the effectiveness of the consolidation program.

The same sequential approach is followed for secondary holes. After each secondary hole is drilled, core is reviewed in the field to confirm grout migration from adjacent primary holes. Visible grout in the core is a key indicator that pressure grouting has been effective. If no grout is observed in the core, hole spacing may be too wide, grouting pressures may be too low, or the ground conditions may not be conducive to ground consolidation. In these cases, additional holes may need to be drilled reactively, and the grout ring design or grouting methodology should be reviewed for future applications.

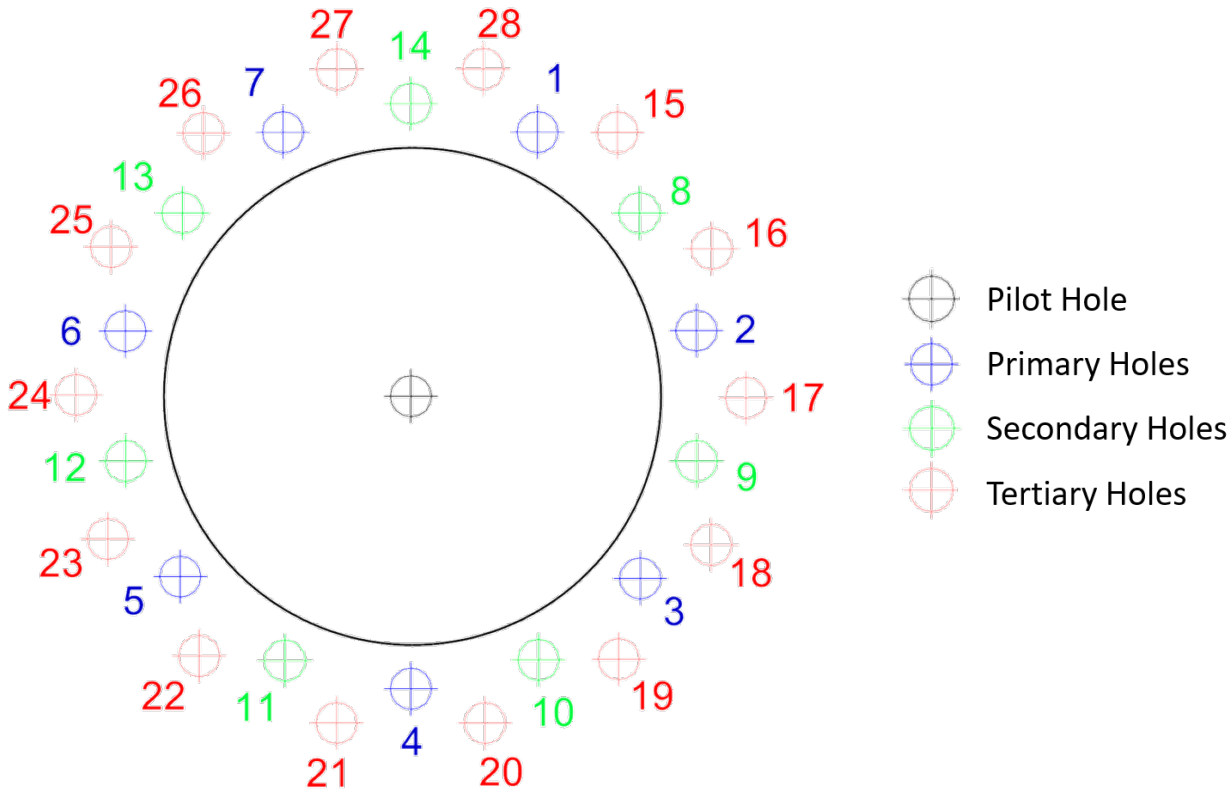


Figure 4 Grout ring design for a 3.6 m raise showing the pilot hole (black) and primary (blue), secondary (green) and tertiary (red) hole locations with respect to each other, and the raise itself

The spacing between primary and secondary holes is a critical design parameter that needs to be refined based on site-specific conditions and field observations. Hole spacing, and subsequently the number of holes, is determined by several factors:

- Raise diameter: larger diameter raises require more holes to maintain consistent hole spacing around the raise perimeter and ensure adequate grout coverage.
- Ground conditions and structures: hole spacing needs to account for discontinuities, fracture frequency, infill material, and overall permeability of rock mass. Hole spacing may need to be increased or decreased to ensure sufficient grout migration through rock mass defects.
- Field observations: observed grouting pressures, visible grout in secondary hole core and visible grout in drill cuttings provide valuable indicators of grout migration. These observations should be used for refining grout ring designs and can also be used reactively to adjust hole spacing in the field.

Grout ring hole spacing at Kennecott has been refined through an iterative process to achieve a balance between effective ground consolidation, and schedule and cost savings. Grout rings for a 3.6 m diameter vent raise typically comprise 7 primary holes, 7 secondary holes, and where required, 14 tertiary holes. For 1.8 m diameter escapeway raises, grout rings generally consist of 4 primary holes, 4 secondary holes, and, where required, 8 tertiary holes. While this represents the standard design, the number of holes can be adjusted based on grout migration observations in the field. For example, grout rings recently drilled at Kennecott for a 3.6 m diameter raise were reduced from 7 primary and 7 secondary holes to 6 primary and 6 secondary holes after grout migration indicated that effective consolidation could be achieved within the lithology using fewer holes (Figure 5). Although designs may be modified slightly based on field observations, grout rings are typically designed 0.3 m outside the raise perimeter, with approximately 1 m hole spacing between primary and secondary holes (Figure 6).



Figure 5 Completed grout ring for a 3.6 m ventilation raise comprising a modified design of 6 primary holes and 6 secondary holes. Margo packers/grout packers indicate the location of each hole

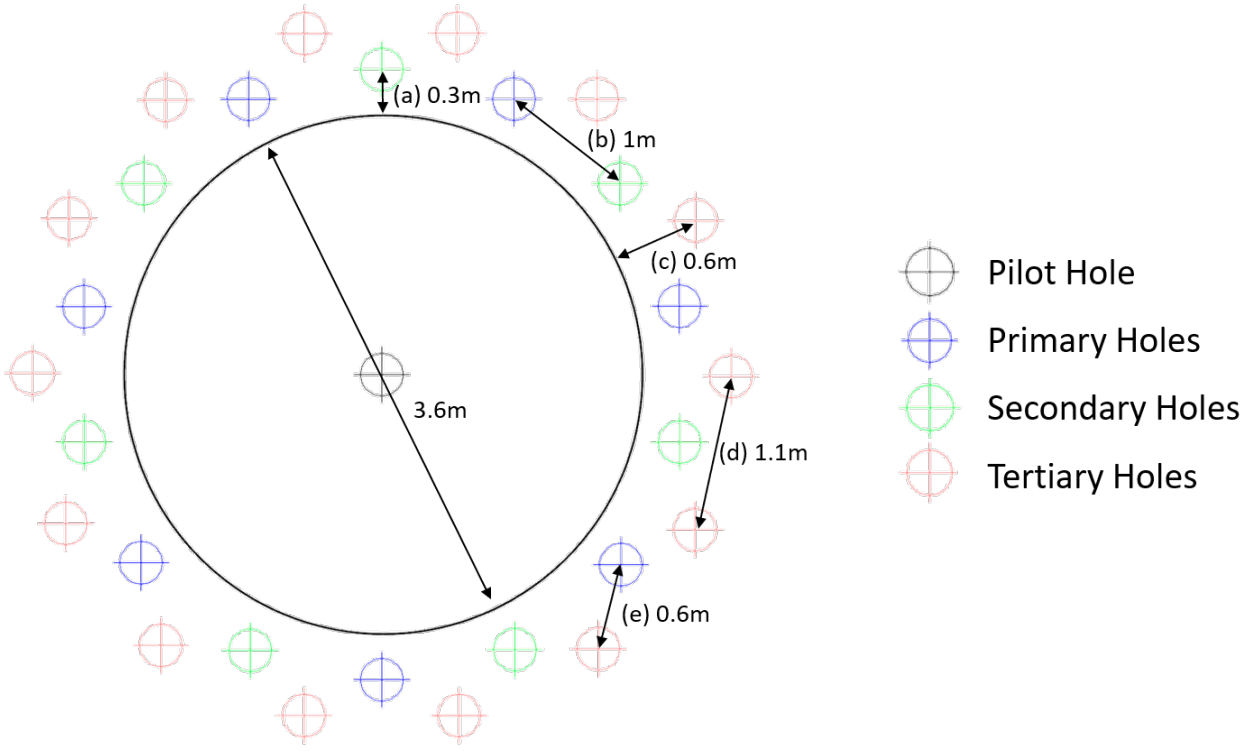


Figure 6 Grout ring design showing spacings between (a) primary/secondary holes and the raise, (b) primary and secondary holes, (c) tertiary holes and the raise, (d) tertiary holes, and (e) primary/secondary holes and tertiary holes

4.1.2 Hole length

Primary grout holes are designed to extend the full length of the raise and into planned bottom cut development. This ensures the raise brow is consolidated and improves stability in the area of the raise that will remain unsupported for the longest period. It is crucial that the bottom cut is not developed until grout rings have been completed. If the bottom cut has been developed prior to grout rings, several challenges may arise:

1. Primary holes need to be designed shorter and the raise brow doesn't get consolidated
2. Primary holes are drilled to depth and grout runs out into the bottom cut during grouting, or
3. The bottom of the primary holes need to be plugged adding complexity and cost to the process.

To avoid these issues, design holds are placed on bottom cut development approximately 20 m short of the raise footprint and not lifted until the grout rings have been completed.

Secondary grout hole lengths are designed with consideration of the geology intersecting the raise footprint (Figure 7). Holes extend well beyond the location where poor ground or structures intersect the raise to ensure maximum grout migration in the zones that require consolidation the most.

Where recommended, tertiary grout holes are designed using the same principle as secondary holes, with a primary focus on improving ground conditions at the raise collar. Given that personnel work around the raise collar following raiseboring, the requirement for tertiary holes should be assessed conservatively. Where raise collars are designed in widespread areas of poor ground, Kennecott has found success with 10 m long tertiary grout holes. When a structure intersects the collar, holes are designed to specifically target that feature. When multiple structures intersect a raise, the secondary and tertiary grout hole programs are designed in conjunction to ensure the structures are being consolidated in the most effective way.

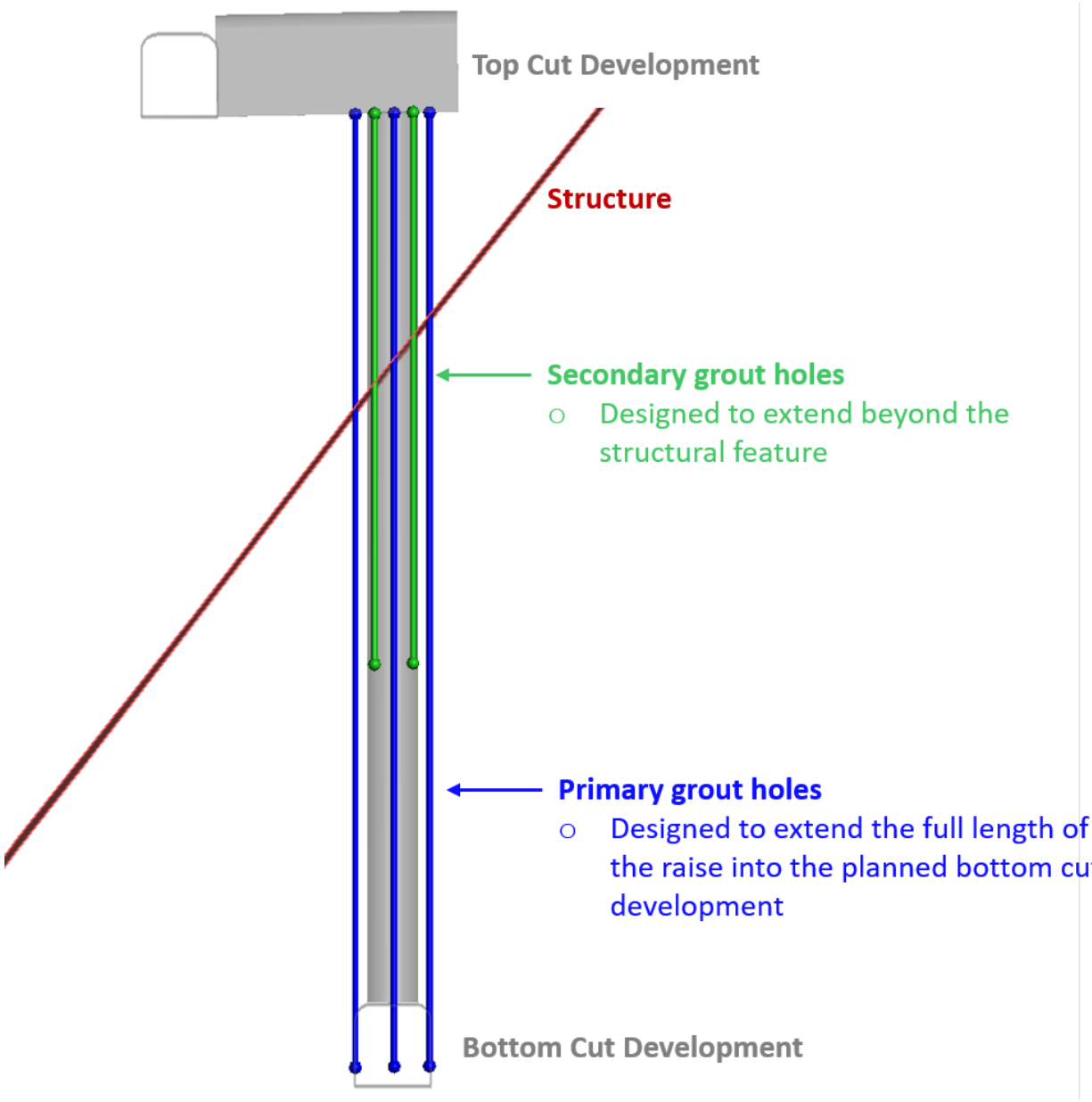


Figure 7 Cross-section of a grout ring design showing the lengths of primary and secondary grout holes

4.1.3 Operational considerations

The execution of drilling and pressure grouting is as critical to success as the grout ring design itself. While the geotechnical cover hole is always drilled with a diamond drill rig, grout rings can be drilled with either a diamond drill rig or a production (ITHH/TH) drill rig. Where possible, diamond drilling is preferred, as it minimises hole deviation and provides core that can be reviewed to assess ground conditions and confirm grout migration. However, for short, low risk raises where the potential for hole deviation is low, production drilling offers a more cost and time effective alternative. Whichever rig does the drilling is ultimately a trade-off between drilling accuracy, time, and cost.

During drilling, hole deviation is monitored and reported, as excessive deviation can reduce consolidation coverage and potentially result in holes intersecting the planned raise footprint. Ideally, all grout ring holes should be surveyed; however, this is not always practical or feasible.

After the geotechnical cover hole has been drilled, it is high pressure grouted with ultrafine grout. This consolidates the rock mass in the centre of the raise and provides the pilot hole, which is drilled at the same dip and azimuth, the best opportunity to remain open and stable. When pressure grouting cover holes

and grout ring holes, it is critical to understand the grouting pressure required to achieve grout migration into the surrounding rock mass. Through experience and continued refinement at Kennecott, a minimum grouting pressure of 5 MPa has been established as the threshold required to provide confidence that grout has penetrated into the surrounding rock. While this pressure has worked well for previous raises, the required pressure may change with mining depth, stress conditions and geological formations.

During grouting, pressure remains below 5 MPa while the drillhole itself is being filled. Once the hole is full and grout begins to penetrate into the rock mass, pressure begins to increase. Grouting continues until a pressure of 5 MPa is achieved, at which point the pressure is released and the grouting crew moves on to the next hole.

Understanding the theoretical volume of each drillhole is important. It allows grout crews to correlate grout volumes, pressure readings, and the amount the hole has been filled. As the theoretical hole volume approaches 100% and pressure starts to increase, it is a strong indicator to crews that grout is beginning to penetrate into the rock mass. Comparing the theoretical hole volume with the total grout volume pumped also provides an indication of the amount of grout that the rock mass took, which subsequently indicates the extent of consolidation. Pressure grouting records, including grout volumes and achieved pressures, should be provided to the geotechnical team for reconciliation, back-analysis, and optimisation of grout ring designs.

4.2 Bottom cut cable bolts

Installing bottom cut cable bolts around the perimeter of the raise is standard practice within the mining industry to provide additional reinforcement in the raise brow. At Kennecott, cables are only installed once the pilot hole has been drilled to ensure they are not accidentally placed inside the raise footprint. Once the pilot hole has broken through, the survey department mark up a stand-off distance between the raise perimeter and planned cable locations, which is typically one metre (Figure 8).

Drilling accuracy is also critical during cable installations to ensure they are not installed within the raise footprint. Cables are designed and installed with a 10° dip away from the raise to reduce the potential for installation errors or hole deviation into the footprint. If the raisebore head becomes tangled in cable, damage to the reaming head, rods and other equipment could occur. These delays can result in the raise sitting unsupported for extended periods of time, which increases the risk of instability.

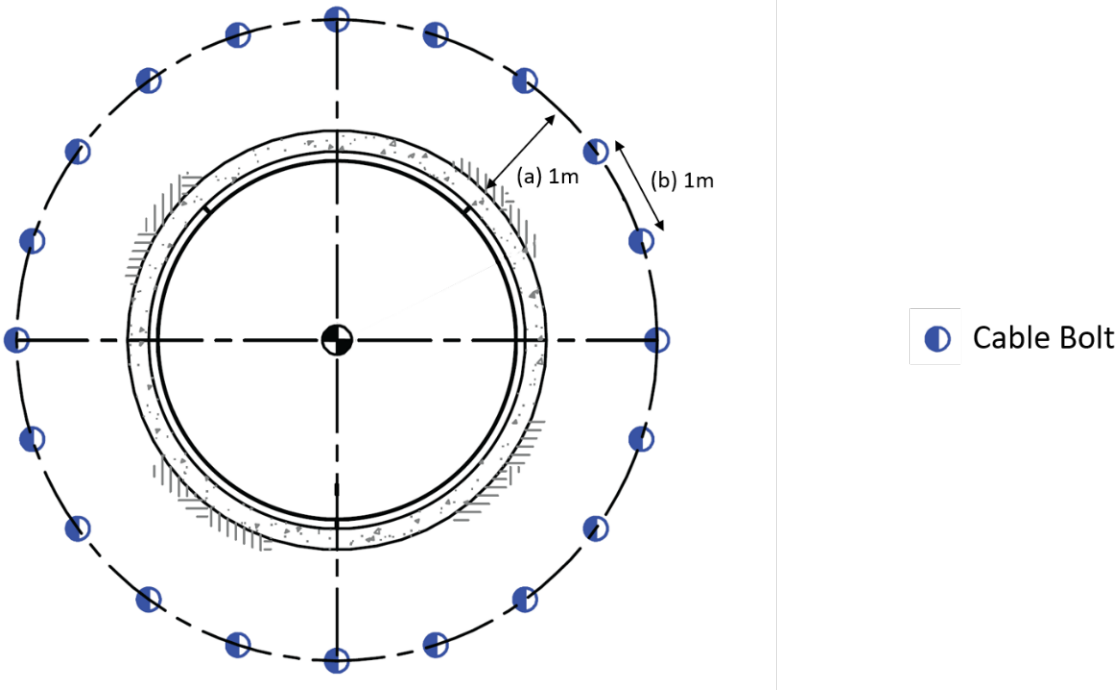


Figure 8 Bottom cut/raise brow cable bolt design

4.3 Key learnings

Vertical development at Kennecott has highlighted several key learnings with respect to pre-support methods:

1. Primary and secondary holes are critical for achieving effective ground consolidation around a raise perimeter. Tertiary holes are generally only required where poor ground conditions have been identified near the raise collar.
2. Grout ring holes should be drilled and grouted sequentially (e.g. drill and grout hole #1, drill and grout hole #2, and so forth). While drilling all holes prior to grouting may be tempting, it increases the risk of inadvertently grouting adjacent open holes. This can result in re-drilling, increased costs, schedule delays, and an inability to achieve the target grouting pressures required for effective grout penetration and rock mass consolidation.
3. Hole spacing should be tailored to site conditions and consider factors such as raise diameter, discontinuities, fracture frequency, infill material, rock mass permeability, field observations, and lessons learned from previous grout rings.
4. Secondary hole core should be reviewed during drilling to assess grout migration. Visible grout in the core is a key indicator that pressure grouting has been effective. No grout in the core indicates that hole spacing may be too wide, grouting pressures may be too low, or ground conditions are not amenable to ground consolidation.
5. Primary grout holes should be designed to extend the full length of the raise and into the planned bottom cut to ensure the future raise brow is consolidated. A design hold should be put on the bottom cut ~20 m before the planned raise, and development scheduled for after the grout rings have cured.
6. Secondary and tertiary grout rings should be designed with consideration of the geology intersecting the raise footprint. Holes should extend beyond the location where poor ground or structures intersect the raise to ensure consolidation is occurring in areas that need it most.
7. Hole deviation needs to be monitored during drilling to ensure adequate consolidation coverage is achieved and to confirm holes remain outside the planned raise footprint. Ideally, all grout ring holes should be surveyed; however, this is not always practical or feasible.
8. After the geotechnical cover hole is drilled, the hole should be pressure grouted and the pilot hole drilled along the same dip and azimuth. This improves the likelihood of maintaining a stable and open pilot hole throughout raiseboring.
9. The minimum grouting pressure required to provide confidence that grout is penetrating into the surrounding rock mass needs to be well understood. At Kennecott, experience has shown that a minimum pressure of 5 MPa is required to achieve effective grout migration; however, this may change with mining depth, stress conditions, and geology.
10. Bottom cut brow cables should only be installed once the pilot hole has broken through to minimise the risk of cables accidentally being installed within the raise footprint.

5 Raiseboring

While this paper is not intended to focus on the mechanics of raiseboring, the successful completion of 11 raisebored excavations in poor ground at Kennecott has highlighted several key lessons learned:

1. The reamer head should be kept moving and should not stop for any reason, including shift change. Stopping increases the risk of the head getting stuck, particularly in poor ground conditions, as also highlighted by Eledbro et al. (2019).
2. A low rotation speed and steady, consistent pull rate should be maintained throughout raiseboring. Under no circumstances should the pull rate suddenly be increased, even if ground conditions

improve. Maintaining a low rotation and consistent pull rate keeps the reamer head tight against the raise 'face' providing confinement. If rotation speed or pull rate is too fast, the reamer head can bounce or develop slack, creating a free face for the unconfined rock mass to fail into. Kennecott has had success with a conservative raisebore rate of 4 m per shift in poor ground conditions.

6 Post-support methods

When raiseboring, it is best practice to support the excavation as soon as development is complete, especially in poor ground. Leaving a raise unsupported for an extended period increases the risk of instability which can lead to excessive overbreak, failure along adverse geological structures, or in severe cases, abandoning the raise. Such failures can be costly to remediate and can lead to significant schedule and production delays.

6.1 Spray lining/fibre-reinforced shotcrete lining

At Kennecott, spray lining is recommended as the long-term ground support method for ventilation raises developed in good to moderate-poor quality rock mass. Spraying commences as soon as practical after the raisebore head has been removed and continues uninterrupted until the entire raise has been supported. It is essential that this is built into the mine plan to ensure that crew scheduling for hot seating is arranged, and delays to the mine plan are captured. Due to blast clearance requirements, continuous spraying operations may temporarily affect mine development and production activities. However, these short-term disruptions are preferable to the potentially significant consequences of raise instability or failure.

Operationally, the key considerations during spray lining are similar to spraying applications during lateral development. The fibre-reinforced shotcrete (FRS) mix is applied in accordance with design specifications to ensure good adhesion to the raise walls and to minimise rebound. Appropriate QA/QC procedures are implemented throughout the process, including the collection and testing of FRS samples to verify compliance with design requirements and confirm early-age and ultimate strengths. Consistent FRS thickness is applied across the entire length of the raise. Scans are completed before and after spraying to verify liner thickness and ensure adequate coverage is achieved, particularly in areas of poor ground.

6.2 Steel lining/raise cans

For life of mine ventilation raises developed in very poor ground conditions, steel cans are recommended to improve long-term stability and extend the service life of the excavation. For secondary egress escapeways, modified steel cans with ladders/stairs are installed. In both applications, cans are lowered into the raise and grouted in place to provide a stable and durable lining.

6.3 Key learnings

Experience from post-support methods at Kennecott has highlighted the following key learnings:

1. In poor ground conditions, it is critical to install spray lining or steel lining as soon as the raisebore head has been removed. Any delays in support installation increase the likelihood of overbreak, instability, and in extreme cases, raise failure.
2. Once spraying starts, it should continue uninterrupted until the raise has been fully supported. To facilitate this, hot seating arrangements and any associated impacts to development and production activities should be incorporated into the mine plan.
3. The FRS mix should comply with site design specifications and QA/QC should be completed throughout the process. Scans should be completed before and after spraying to validate FRS thickness, particularly in areas of poor ground.

7 Conclusion

The structurally complex and highly variable ground conditions at Kennecott present geotechnical challenges, particularly for vertical development. Following a raise failure in 2022, a comprehensive risk management approach was implemented, incorporating detailed geotechnical assessments, pre-support measures, controlled raiseboring practices, and rapid post-support installation. Since its implementation, 11 raises have been successfully completed without any significant instability during development.

Among the controls implemented, grout rings have proven to be highly effective in improving vertical development stability and extending the stand-up time of raises. Where possible, raises are mined in competent ground and stability risk is managed through mine design rather than pre-support and post-support measures. Where raiseboring through poor ground is unavoidable, experience at Kennecott demonstrates that proactive ground consolidation, combined with stringent geotechnical controls and disciplined operational practices, can reduce the risk of instability and improve the likelihood of successful raiseboring.

Disclaimer

The practices described in this paper reflect experience gained under the geological and operational conditions at Rio Tinto Kennecott and should not be interpreted as universally applicable engineering requirements. Site-specific geotechnical assessment remains essential.

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