Raisebore stability and support at deep depth and highly defected rock mass condition: Oyu Tolgoi case study

J Ooi *Rio Tinto, Australia*

G Watt *Rio Tinto, Australia*

H Grobler *Oyu Tolgoi LLC, Mongolia*

Abstract

Oyu Tolgoi (OT) has over 50 raises bored to support the ventilation and material handling for the block cave. Mining of the raisebores occurred at depths of 1,200 m to 1,400 m below the surface, in varied rock mass conditions, on the outer limit of the empirical database updated in 2018 by Penney et al. The stability performance of the raises was considered against the empirical predictions for stability during the early design stage, but site performance was used to improve the design process.

Due to faults and defects in the rock mass, the related compressive strength of the rock mass is low relative to the local in situ state of stress and many raise excavations were predicted to be unstable and artificial support was designed. Different pre-support methods were implemented, including spiling using diamond drill steel tubes and resin pressure injection, as well as surface support after excavation, including remote shotcrete and installation of steel cans as lining. Learnings from the support installed were captured to optimise supporting future raises and further enhance knowledge of the response from the different lithologies. An updated design and planning workflow was implemented to assist in the planning and design of support to assist the stability of bored raises.

Geotechnical investigation holes are important to ensure the raise stability is properly assessed and mitigation measures are executed. Good collaboration between different teams is imperative to ensure the design and planning objectives are understood and incorporated as design and planning basis, which then reduces the risk of schedule and cost overrun.

Keywords: raise boring, raise support, deep raisebore, high stress, rock defects

1 Challenges in raiseboring

There are different ways to excavate the vertical raise, and raiseboring is a type of mechanical excavation method via specialised machinery, i.e. raiseborer. The raiseborer is set up on the upper level of the two levels to be connected, on an evenly laid platform (typically a concrete pad). A small-diameter hole (pilot hole) is drilled to the level required; the diameter of this hole is typically 230–445 mm, large enough to accommodate the drill string. Once the drill has broken into the opening on the target level, the bit is removed and a reamer head of the excavation's required diameter is attached to the drill string and raised back towards the machine. The drill cuttings from the reamer head fall to the floor of the lower level.

Due to the nature of raiseboring, the rock mass support can only be installed after the whole length of the raise has been excavated. In other words, vertical walls are left unsupported until the raiseboring is completed. The risk associated with raiseboring is weak rock mass or local structures that may fail during excavation, and potentially jam the reamer head, or unravel completely depending on the structural orientation and local stress magnitudes and direction. In a worst-case scenario, a raise may completely cave if the rock mass is very unstable, meaning a new raise must be excavated and the rock mass rehabbed. It is imperative to understand the local geology before excavation to prevent this failure, which can be costly to rehabilitate.

2 Oyu Tolgoi

In the South Gobi region of Mongolia, Oyu Tolgoi (OT) is one of the world's largest known copper and gold porphyry deposits, situated approximately 550 km south of the capital, Ulaanbaatar, and 80 km north of the Mongolia-China border (Figure 1). OT is jointly owned by the Government of Mongolia, which has 34% ownership, and Turquoise Hill Resources, which owns 66%. Rio Tinto owns 50.8% of Turquoise Hill Resources and provides management services and other critical support for the operations.

Figure 1   **Location of Oyu Tolgoi in the South Gobi region and its proximity to the Mongolia-China Border (Thomas et al. 2020)**
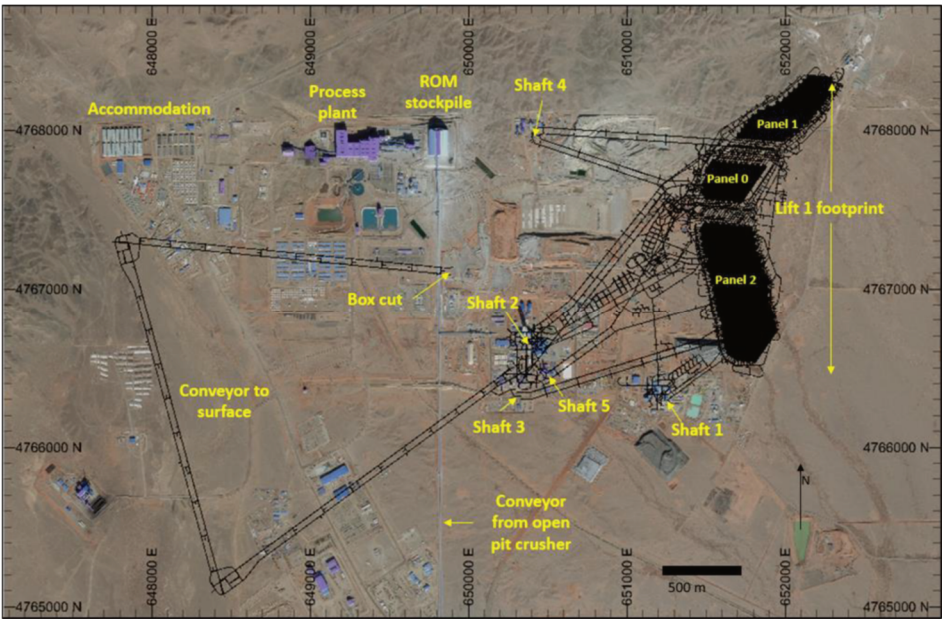
Figure 2   **Hugo North Lift 1 surface infrastructure arrangement, with underground mass mine design as underlayer**

Open pit mining began at Oyu Tolgoi in 2011 and the copper concentrator—the largest industrial complex ever built in Mongolia—began processing mined ore into copper concentrate in 2013. The Hugo North Lift 1 mine design (Figure 2) consists of 211 km of lateral development, five shafts, and twin-decline tunnels from the surface. The primary life-of-mine ore-handling system will transport ore to the surface by a series of conveyors. The underground mass development was initiated with a development shaft (Shaft 1) in 2006, and with early development works running until 2013. After a hiatus, the underground mass development continued from 2016. Currently, the twin-decline tunnels from the surface are developed, three shafts are fully equipped and operational, and 113 km of underground mass development is completed.

The Hugo North orebody is approximately 225 m wide, 2,000 m long, and 1,000 m high, and divided into two lifts. Caving was selected for OT due to the large orebody and generally fair rock mass conditions, with the average Mining Rock Mass Rating (MRMR) being 40–45. Lift 1 is separated into three Panels with a lift height of ~500 m, where the cave is to be initiated at Panel 0. The predicted critical hydraulic radius for P0 caving is 20–23 m, due to the highly faulted at Panel 0.
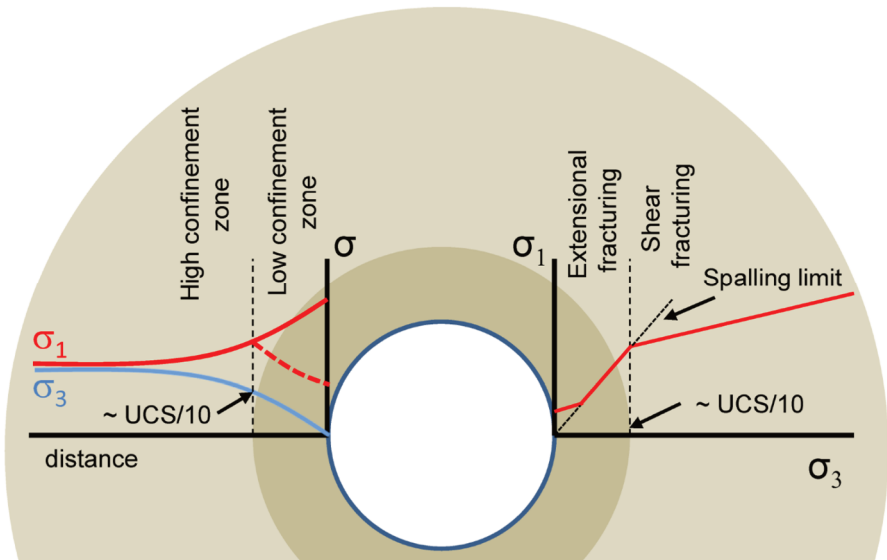
3 Geomechanical characteristics

3.1 Duality nature of defected rock

Much of the rock at OT is moderate to heavily micro-defected and veined (Figure 3). The core often breaks easily along these defects when handled. However, the rock will undergo shear fracturing under high confinement stress and behave similarly to a massive intact rock mass. This duality nature where the intact strength is dependent on the degree of confinement – low confinement yields low intact strength and high confinement yields high intact strength – exhibit challenges for raisebores in term of analysis and operation.

(a)   (b)

Figure 3   (a) Veined and defected core; (b) Heavily micro-defected core. Veins appear as thicker white features; micro defects appear as black hairline features

Figure 4 illustrates the rock behaviour surrounding the circular tunnel (in this case raisebore). Near the excavation boundary of the raisebore where low confinement stress, the veins and micro-defects dilate and open, which then unravel due to the inability to install support during raiseboring.

Raisebore stability and support at deep depth and highly defected
rock mass condition: Oyu Tolgoi case study
J Ooi et al.

Figure 4 Left side of the circular tunnel: Typical distribution of stresses (tangential σ_1 and radial σ_3 stress) according to Kirsch solution. When failure occurs, the tangential stress σ_1 drops as indicated by the red dashed line. The right side of the circular tunnel: typical failure envelope of brittle rock with pre-dominant extensional fracturing at low confinement and macroscopic shear fracturing at high confinement (after Bewick 2021)

3.2 In situ principal stress

Due to the tectonic setting near OT, it is not reasonable to use a linear fit to data, by forcing it through zero at zero depth. In the tectonically strained rock mass, the horizontal stresses are elevated by a constant amount over a depth range where the strain is constant and stress relief along faults does not occur. Based on studies in many parts of the world (e.g. the Canadian shield) it is found that there is a stress relieved zone near the surface and a tectonically strain-controlled zone at depth (a depth-independent strain or stress increment added to a gravitational gradient). In between is a transition zone (typically related to macrostructure), where very high strain gradients may be encountered (Maloney et al. 2006; Martin et al. 2003). OT exhibits similar characteristics, where the Contact Fault is the transition zone. Figure 5 illustrates the comparison of the Canadian Shield and Oyu Tolgoi stress regime. The sub-horizontal major principal stress (σ_1) bearing towards 54°, intermediate principal stress (σ_2) is vertical, and minor principal stress (σ_3) is bearing toward 144°. At the production level at 1,300 m, where the predominately raisebores are located, the $\sigma_1 = 58$ MPa, $\sigma_2 = 33$ MPa and $\sigma_3 = 27$ MPa, and the K ratio of 1.75. Table 1 outlines the stress regime and field gradient.

Table 1 The OT in situ principal stress regime, where all the raisebores are located in stress domain 3

| OT stress domains	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)	Depth range, z (m)
Domain 1	0.047z	0.0265z	0.024z	0–600
Domain 2	0.071z - 13.95	0.0265z	0.027z - 1.59	600–800
Domain 3	0.031z + 17.50	0.0265z	0.015z + 7.66	>800
Bearing angle (°)	54	Vertical	144	
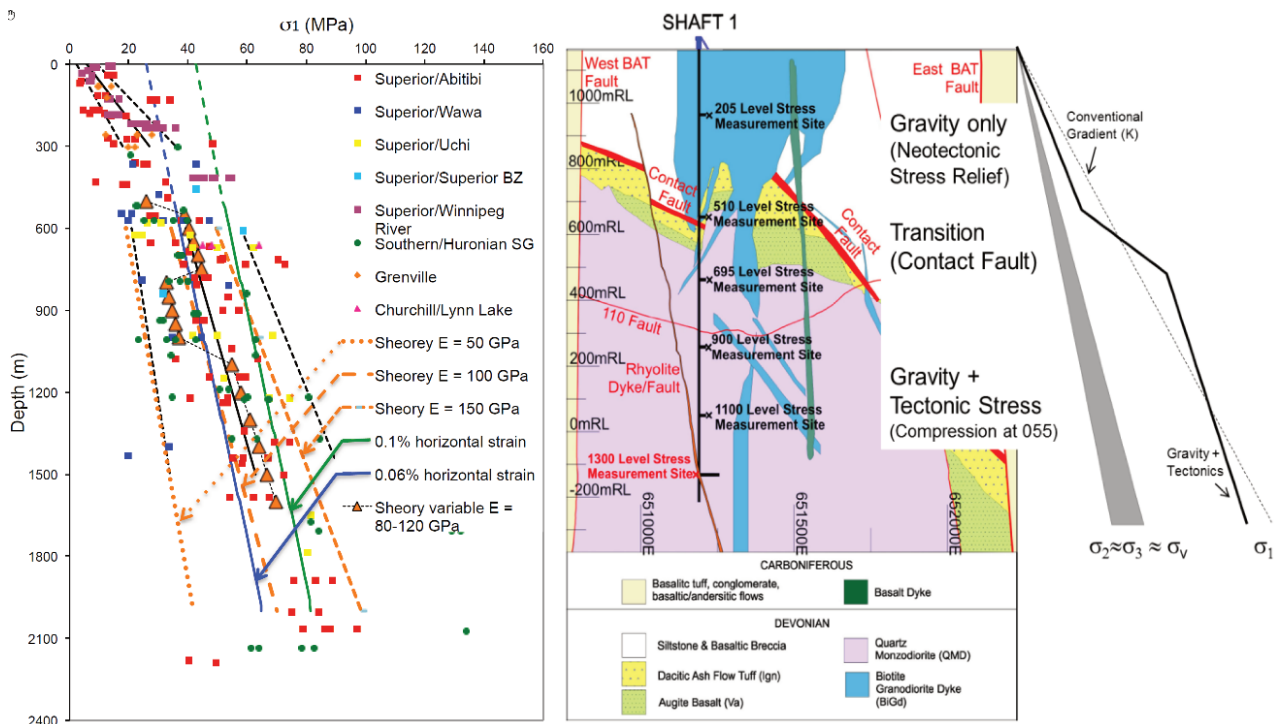
Figure 5 Stress data from the Canadian Shield on left (after Kaiser et al. 2016) and Oyu Tolgoi interpretation stress regime on right

3.3 Rock mass characterisation

OT's rock mass characterisation is based on geotechnical domains, which can be defined by a combination of the main geological elements, including lithology, alteration, and mineralisation (Flores & Karzulovic 2003). The geotechnical properties that govern the behaviour of the different geotechnical domains at OT are primarily lithology and alteration. Rock mass strength parameters were determined for each domain based on intact rock testing and face mapping data, particularly for IRMR. Results emphasised the highly fractured nature of the Hugo North rock mass, particularly the intensity of the veining, which will serve to reduce the rock block strength. Table 2 outlines the intact rock mass properties and Figure 6 illustrates the lithology and alteration domains at the extraction level, overlays with the fault damage zone.
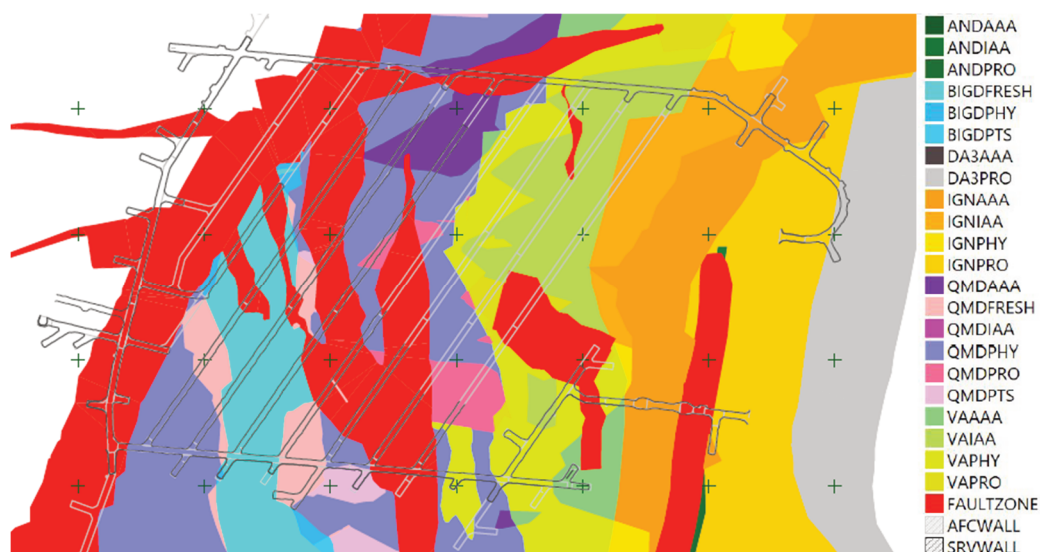

Figure 6 Lithology and alteration domains distribution for the extraction level, as well as modelled fault zones with the thickness representing fault damaged zones

Table 2   OT's rock mass properties

Lithology	Alteration	Intact rock strength properties		
		σ_{ci} (MPa)	m_i	σ_t (MPa)
Biotite granodiorite (BIGD)	Unaltered (low vein density)	114	12	3.7
	Unaltered (high vein density)	84	12	5.5
Quartzite monzodiorite (QMD)	Advanced argillic (AAA)	56	16	2.8
	Intermediate argillic (IAA)	75	21	3.5
	Phyllic (PHY) (low vein density)	86	19	5.5
	Phyllic (high vein density)	65	24	3.3
	Potassic (PTS), propylitic (PRO)	94	24	3.3
Basalt lava flows (BASL)	Propylitic	91	28	3.1
Basaltic tuff (BAT)	Propylitic	29	18	1.3
	Unaltered	83	19	3.8
Basaltic flow breccia (L)	Metamorphic, propylitic	74	19	3.8
Sandstone – slitstone (SST-SLT)	Unaltered	60	13	3.5
Dacite (DACL)	Unaltered	67	13	2.2
Dacitic block ash tuff (VBX)	Unaltered	45	17	1.3
Ignimbrite (IGN)	Advanced argillic	72	11	5.1
Augite basalt flow and breccias (VA)	Advanced argillic	65	17	2.1
	Intermediate argillic	66	24	3.6

4   Planning and execution workflow

It is imperative to understand the nature of works required for raisebore, including the potential mitigation works should the raise fail. Failure to anticipate the nature of the work required will result in significant schedule delays and cost overblown. However, it is often difficult to understand the risky nature of the raisebore until the investigation diamond drillhole is completed, which is often during the execution stage of the project and often there is minimal room for schedule and budget modification. In addition, OT mine design consists of >200 counts of vertical raises, which may complicate the planning process. To overcome this, OT developed a workflow that covers the different engineering stages – design, planning and execution – to capture the holistic overview of planning work packages, which also include potential mitigation measures (Figure 7).
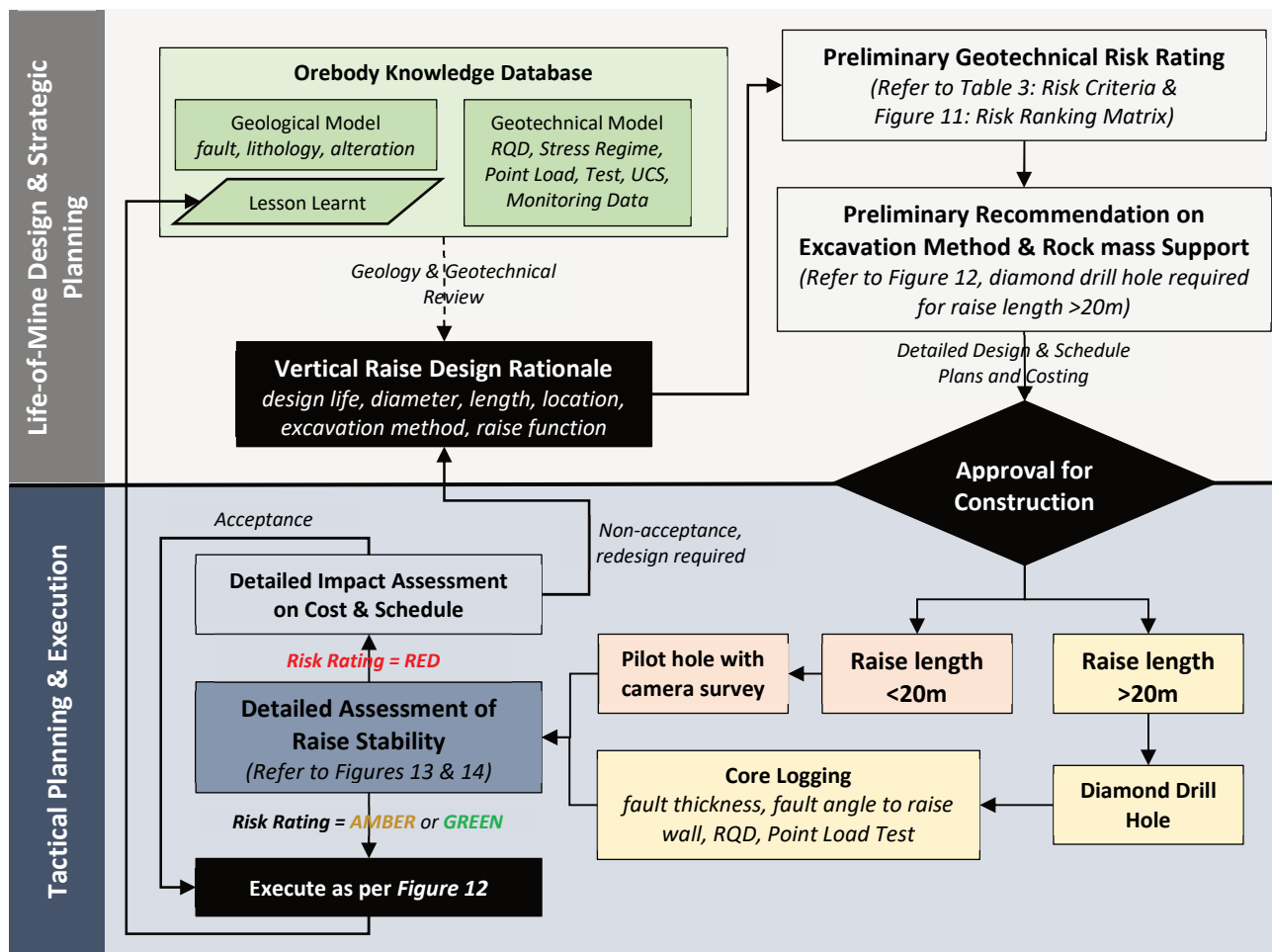
Figure 7   Generalised design and planning flowchart for raisebore at OT

4.1   Design and strategic planning

It is challenging to estimate the raisebore stability during the initial phase of the engineering stage (life-of-mine design and planning), where the understanding of rock mass can often be low confidence, but it can estimate the level of work package (in terms of excavation method and rock mass support requirement) via the quasi-empirical method, where each potential raisebore designed is assigned a geotechnical risk rating based on four criteria:

1. Proximity to fault or lithology contact (controlling unravelling stability risk during raiseboring).

2. Proximity to cave footprint (long-term stress-induced stability).

3. Proximity to surrounding excavation (pillar distance between raisebore to surrounding excavations).

4. Raise function (to determine the rock mass support allocation strategy and design life).

4.1.1   Criterion A – proximity to fault or lithology contact

The fracture frequency is increasing at an exponential rate when approaching major faults (Figure 8), as this is due to an increasing intensity in veins, defects and joints, which further results in a lower Q_r value. At OT, the mapped tunnel face has observed lower rock quality designation (RQD) when it is ~25 m away from faults or lithology contact. With higher fracture frequency, the rock is highly jointed and increases the risk of raise wall failure (unravelling or damaging cutter head) during raiseboring. This will then further challenge the effectiveness of mitigation and could potentially lead the raise to be abandoned, which is putting pressure on cost and project budget.
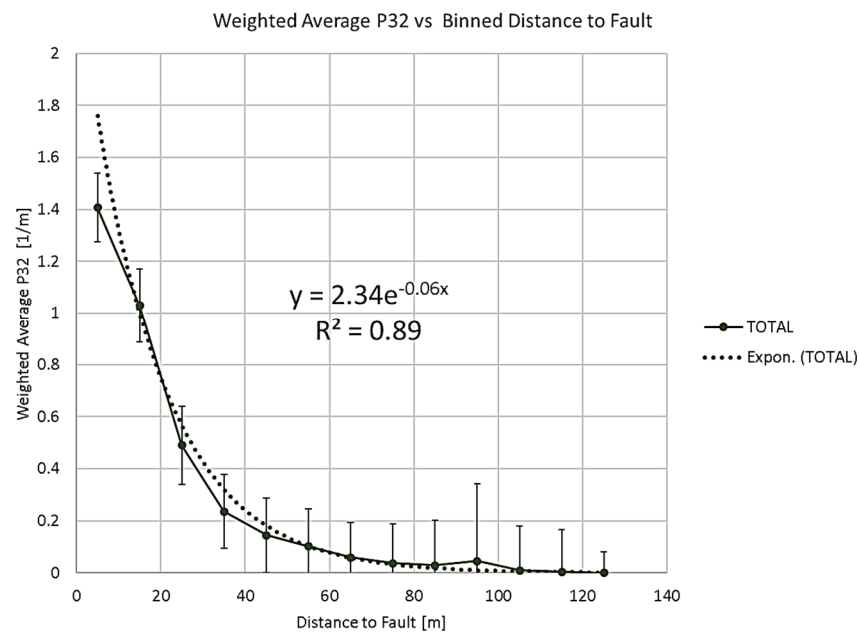
Figure 8 A review of core data at OT shows that veins intensity (P32) increased exponentially when measured distance to the modelled fault

4.1.2   Criterion B – proximity to cave footprint

The stress change is to be considered as most of the vertical raises are located near the production footprint, which then further influences the rock mass support design. As the cave grows, the abutment stress induced by caving will be imposed on the surrounding cave boundary, where the stress magnitude can be up to 110 MPa at the cave boundary, a 90% increase in comparison with in situ stress of 58 MPa (Figure 9). If the location of the raise is planned within 100 m of the raise, it will be subjected to a higher magnitude of stress change, depending on the location, and the impact of stress change is less pronounced when moving away from the cave boundary.
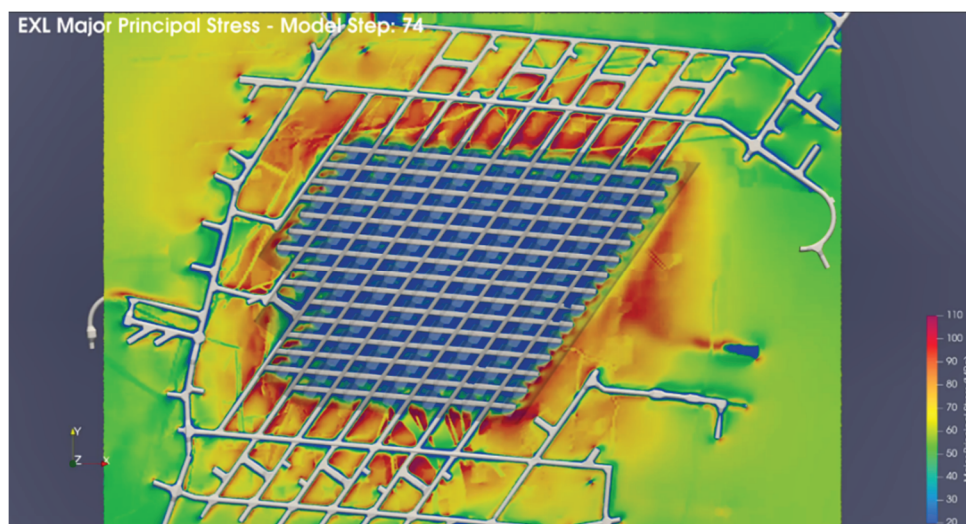

Figure 9 Cave abutment stress up to 110 MPa is estimated at extraction level when the cave is fully developed, as estimated by numerical modelling

4.1.3   Criterion C – proximity to surrounding excavation

Any excavation generates a localised stress field that concentrate around its boundary, where high tangential stress peak near the immediate boundary, then further decrease to similar in situ field stress at approximate three times of the span. The position of raise shall be away from the nearest tunnel, where the distance between raise and tunnel is recommended at approximately three times the width of the excavation, so to avoid stress interaction (Figure 10).
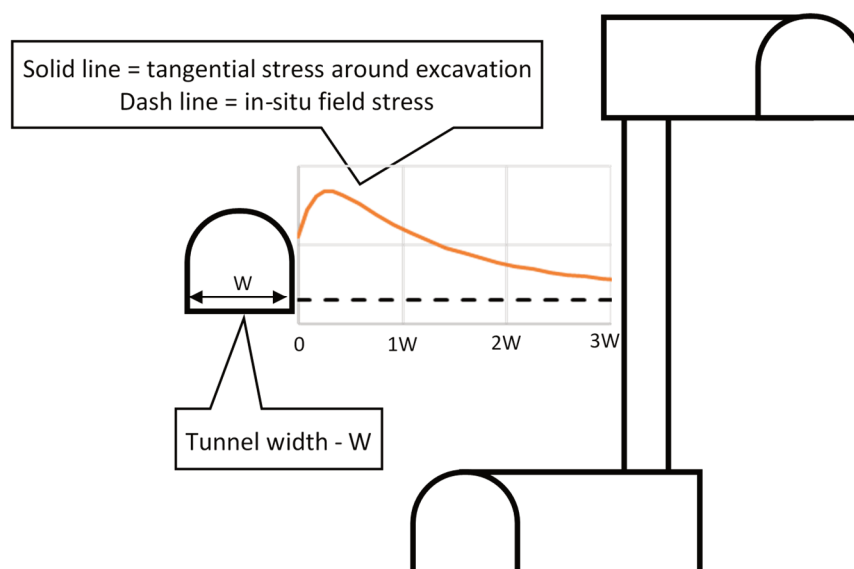
Figure 10   The raise is recommended to be placed at a distance of approximate three times the width of the nearest tunnel. Tangential stress on the tunnel wall, estimated via Kirsch's Equation (Brady & Brown 2005), is shown, where the tangential stress is reduced similar to in situ stress at a distance equal to three times the width of the tunnel

4.1.4   Criterion D – raise function

The planned function of the raise will determine the required rock mass support, as a different type of rock mass support required different effort levels of planning. For temporary ore pass, with the usage of less than one year and low tonnage and located outside of cave footprint (>200 m), will be only lined with shotcrete with 100 mm thickness. For ventilation raises, either permanent or temporary and located outside of the cave footprint, will be lined with shotcrete. Any raises near the footprint (<100 m from cave footprint) will be steel lined.

4.1.5   Risk criteria and planned mitigation measures

Combining all four criteria, the risk rating is then presented in Table 3. A total of 81 possible combinations, which ranked with three different risk categories in Figure 11, where Red is High Risk, Amber is Medium Risk and Green is Low Risk. A list of mitigation measures, with recommended rock mass support and excavation method, is outlined in Figure 12 based on the planned raise location and length. All planned raise lengths >20 m is required an investigation diamond drillhole. Listed mitigation measures in Figure 12 is incorporated into integrated mine planning to ensure the estimated duration and cost are accountable for the whole work package. This then further reduces the likelihood of schedule overrun in case the raise cannot be constructed in the planned time due to unexpected rock mass conditions.

Table 3   Risk criteria for raise design and planning

Risk criterion	1 – High Risk	2 – Medium Risk	3 – Low Risk
A – Proximity to fault or lithology contact	0–10 m or modelled fault intercept the planned raise	10–25 m	>25 m
B – Proximity to cave footprint	In the footprint or 0–100 m from the footprint boundary	100–200 m from footprint boundary	>200 m from footprint boundary
C – Proximity to surrounding excavation	1W–2W	2W–3W	>3W
D – Raise function	Permanent ore pass or ventilation raise	Temporary ore pass	Temporary ventilation raise

Note: W = Width of the nearest and largest excavation size surrounding the planned raise

A1-B1-C1-D1	A2-B1-C1-D1	A3-B1-C1-D1
A1-B1-C1-D2	A2-B1-C1-D2	A3-B1-C1-D2
A1-B1-C1-D3	A2-B1-C1-D3	A3-B1-C1-D3
A1-B1-C2-D1	A2-B1-C2-D1	A3-B1-C2-D1
A1-B1-C2-D2	A2-B1-C2-D2	A3-B1-C2-D2
A1-B1-C2-D3	A2-B1-C2-D3	A3-B1-C2-D3
A1-B1-C3-D1	A2-B1-C3-D1	A3-B1-C3-D1
A1-B1-C3-D2	A2-B1-C3-D2	A3-B1-C3-D2
A1-B1-C3-D3	A2-B1-C3-D3	A3-B1-C3-D3
A1-B2-C1-D1	A2-B2-C1-D1	A3-B2-C1-D1
A1-B2-C1-D2	A2-B2-C1-D2	A3-B2-C1-D2
A1-B2-C1-D3	A2-B2-C1-D3	A3-B2-C1-D3
A1-B2-C2-D1	A2-B2-C2-D1	A3-B2-C2-D1
A1-B2-C2-D2	A2-B2-C2-D2	A3-B2-C2-D2
A1-B2-C2-D3	A2-B2-C2-D3	A3-B2-C2-D3
A1-B2-C3-D1	A2-B2-C3-D1	A3-B2-C3-D1
A1-B2-C3-D2	A2-B2-C3-D2	A3-B2-C3-D2
A1-B2-C3-D3	A2-B2-C3-D3	A3-B2-C3-D3
A1-B3-C1-D1	A2-B3-C1-D1	A3-B3-C1-D1
A1-B3-C1-D2	A2-B3-C1-D2	A3-B3-C1-D2
A1-B3-C1-D3	A2-B3-C1-D3	A3-B3-C1-D3
A1-B3-C2-D1	A2-B3-C2-D1	A3-B3-C2-D1
A1-B3-C2-D2	A2-B3-C2-D2	A3-B3-C2-D2
A1-B3-C2-D3	A2-B3-C2-D3	A3-B3-C2-D3
A1-B3-C3-D1	A2-B3-C3-D1	A3-B3-C3-D1
A1-B3-C3-D2	A2-B3-C3-D2	A3-B3-C3-D2
A1-B3-C3-D3	A2-B3-C3-D3	A3-B3-C3-D3

Figure 11   Risk rating outcome, based on 81 possible combinations of risk criteria from Table 3, coloured with Red – High Risk, Amber – Medium Risk and Green – Low Risk

Risk Rating	Raise Length	Within Cave Boundary (<100m)		Outside Cave Boundary (>100m)	
		<20m	>20m	<20m	>20m
RED	**Mining Method**	Grouted HQ Size bored piles, raise bore	Grouted HQ Size bored piles, BBR	Grouted HQ Size bored piles, raise bore	Grouted HQ Size bored piles, BBR
	Ground Support	Steel Lining	Steel Lining	Steel Lining	Steel Lining
AMBER	**Mining Method**	Resin injection, raise bore	Grouted HQ Size bored piles, Resin injection, raise bore	Resin injection, raise bore	Grouted HQ Size Bored piles, Resin injection, raise bore
	Ground Support	Steel Lined	Steel Lined	100mm Fibrecrete	100mm Fibrecrete
GREEN	**Mining Method**	Drill & Blast or raise bore	Raise bore	Drill & Blast or raise bore	Raise bore
	Ground Support	100mm Fibrecrete	100mm Fibrecrete	Nil	100mm Fibrecrete

Note: BBR – Boxhole BackReaming, is a raise machine that is able to ream and line the raise in parallel, a special collaboration with Rio Tinto and Herrenknecht AG (Herrenknecht AG 2022).

Figure 12   Preliminary recommendation on excavation method and rock mass support for each risk category

4.2   Tactical planning and execution

It is important to understand the rock mass condition before commencing with the raisebore. At OT, for raise length <20 m, the face mapping from the tunnel above and below the planned raise shall be utilised to map any unfavourable structure, which then further advises the excavation method and rock mass support method. For raise length >20 m, an investigation hole by the mean of diamond drill is required. All the investigation works are scheduled and planned at all levels of the OT planning process.

4.2.1   Generalised raisebore stability assessment workflow

Before raisebore, a detailed raisebore stability assessment is conducted to understand the stability risk, where face maps or core log obtained from the investigation hole is utilised. The assessment workflow is as follows.

1. Identify the vertical raise physicals, such as location, orientation in relation to principal stress direction, shape, intended design life, relative distance to surrounding pre-existing or planned excavations and relative distance to major geological features.

2. Identify principal stress magnitude and orientation across the entire length of the vertical raise.

3. Identify the behaviour and characteristics of geological features such as faults, bedding, dykes, and lithological contacts.

4. Conduct rock mass classification and characterisation for the entire length of the vertical raise, based on Tunnel Quality Index, Q (Barton et al. 1974; Grimstad & Barton 1993; McCracken & Stacey 1989; Penney et al. 2018). Note that Stress Reduction Factor (SRF) shall be estimated from Peck (2000).

5. Estimate the stand-up time without rock mass support, as per McCracken & Stacey (1989).

6. Conduct a preliminary assessment of the dominant mode of instability across the intended design life of the vertical raise, based on Brummer (1998), both short-term stability during raiseboring, and long-term stability after raiseboring, based on estimated stress conditions and expected rock mass strength and conditions.

7. Conduct brittle-failure assessment for vertical raise to estimate the depth of damage (Kaiser 2016, 2019).

8. Benchmark the assessment results against the database by Penney et al. (2018) and site experience and observations.

9. If the planned vertical raise is intended to be used as an unlined ore pass, the intended ore pass life can be estimated as per Hadjigeorgiou & Mercier-Langevin (2018).

10. If the planned vertical raise is located within the cave boundary and is expected to undergo different stages of stress change, numerical assessment is required.

11. Revise the excavation method and rock mass support recommendation should the assessment outcome differ from the estimation from Section 4.1.

4.2.2 Detailed assessment criteria

The assessment criteria, mainly based on McCracken & Stacey (1989), is to serve as a guide for in-field engineers to risk rank the raise stability (Figures 13 and 14). Penney et al. (2018) pointed out that the McCracken & Stacey (1989) method is not able to account for stress damage, hence the stress/strength ratio, modified from Kaiser (2016), is adopted in the assessment matrix.

Geotechnical Raise Stability Assessment for Raise Length > 20m				
Risk Rating – RED (High Probability of Failure)				
$Q_r < 1$	$RMR_{89} < 30$	$0.5 < \sigma_1 / \sigma_c < 0.75$	Fault/Shear thickness > 0.2m	Fault present and parallel or sub-parallel to raise axis (0 – 60 degree)
Risk Rating – Amber (Moderate Probability of Failure)				
$1 < Q_r < 2$	$30 < RMR_{89} < 40$	$0.3 < \sigma_1 / \sigma_c < 0.5$	Fault/Shear thickness < 0.2m	Fault present and normal to sub-normal to raise axis (60 – 90 degree)
Risk Rating – Green (Low Probability of Failure)				
$Q_r > 2$	$RMR_{89} > 40$	$\sigma_1 / \sigma_c < 0.3$	No fault or shear is mapped	

Figure 13   Raise stability risk rating matrix for raise length >20 m, where the data obtained from investigation diamond drillhole

Geotechnical Raise Stability Assessment for Raise Length < 20m			
Risk Rating – RED (High Probability of Failure)			
Poor to very poor rock mass (Facemap review at top & bottom raise chamber)	Overbreak observed (>0.5 x hole diameter) from pilot hole	Fault/Shear thickness > 0.2m	Fault present and parallel to raise axis (0 – 60 degree)
Risk Rating – Amber (Moderate Probability of Failure)			
Fair to good rock mass (Facemap review at top & bottom raise chamber)	Overbreak observed (<0.5 x hole diameter) from pilot hole	Fault/Shear thickness < 0.2m	Fault present and normal to sub-normal to raise axis (60 – 90 degree)
Risk Rating – Green (Low Probability of Failure)			
Good to very good rock mass (Facemap review at top & bottom raise chamber)	No overbreak observed from pilot hole	No fault present	

Figure 14   Raise stability risk rating matrix for raise length <20 m, where the data obtained from pilot hole

4.2.3   Excavation method for vertical raise

There are three types of excavation methods for vertical raise; drill & blast (D&B), conventional raisebore and BBR – Boxhole BackReaming. D&B is only used for short vertical raise that <20 m in length, and the risk rating is Green, i.e. good rock mass condition. For raise length >20 m, it is excavated by conventional raisebore machine. Currently OT is trialling BBR, a raise machine that able to ream and line the raise in parallel, a research and development (R&D) collaboration with Rio Tinto and Herrenknecht AG (Herrenknecht AG 2022). Refer to Figure 12 for recommended excavation method based on risk rating and raise length.

4.2.4   Rock mass support for vertical raise

There are two type of rock mass support that is applied to vertical raise: shotcrete liner and steel liner. 100 mm thickness of fibre-reinforced shotcrete is applied to in a raise has a risk rating of Green and Amber for raise located >200 m from the cave (off-footprint), and mainly to ventilation raises. For a raise that has a risk rating of Red and Amber for raise located <200 m from the cave (on-footprint), steel lining is recommended. For vertical raise, the steel liner thickness of 10 mm, while for ore pass the steel liner thickness is 12 mm to provide wearing capacity.

To minimise the overbreak, a series of vertical grouted diamond drill rods (spiling) are installed at the entire length of the raise, where the design of the spiling is based on Sexton et al. (2008). The spile collars are to be installed at an offset of 0.5 m of the perimeter of the raises, with the spacing of the spiles are in the range of 0.5–0.75 m surrounding the perimeter in especially the σ_3 direction and angled 1 degree away from the collar point to avoid intercepting the raise wall (Figures 15).
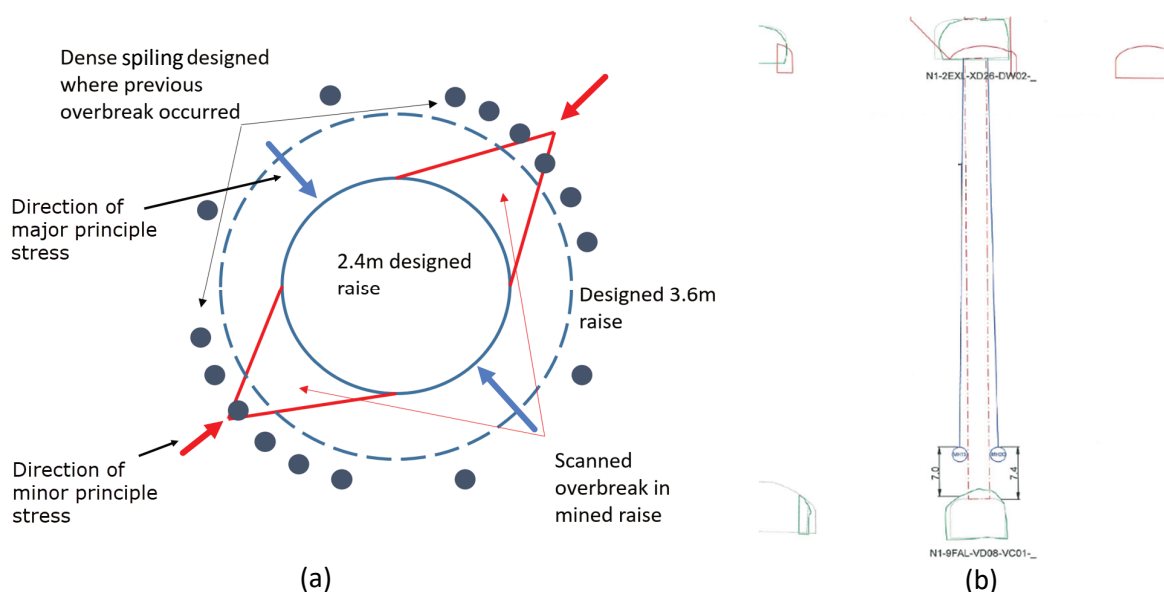
Figure 15   Spiling design: (a) Dense spile spacing at σ_3 direction; (b) Cross-section views of spiles that are installed at 1-degree angle from collar to avoid potential deviation to raise wall

4.2.5   Monitoring techniques

Monitoring is essential to provide validation on design assumptions. Two monitoring techniques are used at OT: borehole camera survey and laser scanning. For the borehole camera survey, the engineer will drop an indicator rope, where every 5 m of the rope is cleared marked, and placed at the north side of the raise. This will help identify the raise breakout direction. For laser scanning, a stationary wire will be dropped at the raise centroid and a Geoslam unit will be lowered along the wire for scanning. The result of the scanning will then further inform the frequency of the raise inspection. Raises that have been observed with significant overbreak (Figure 16) will be monitored monthly before the final lining is installed and the raise that is deemed to be stable will be monitored yearly.
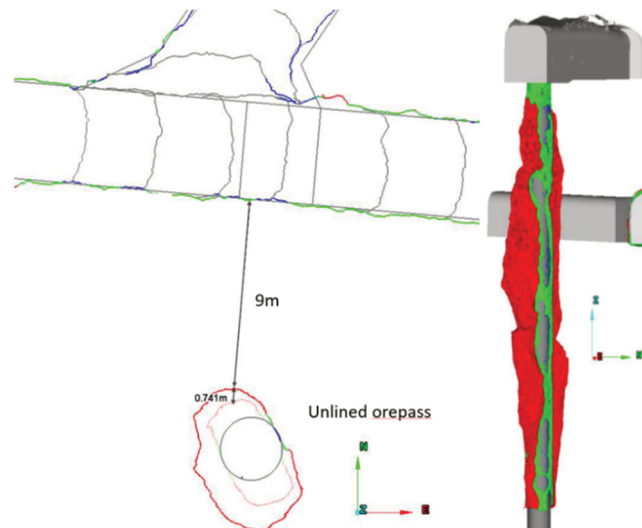
Figure 16 Growth of overbreak of an unlined ore pass from Geoslam laser scanning, from 3 m diameter to 6 m overbreak, measured in the direction of σ_3 of in situ principal stress, resulted in the diminishing pillar between the raise and tunnel

5   Challenges and learnings

5.1   RQD input and SRF in Q_r

RQD input has significant weighting to Q_r. Two RQD values are logged at OT; RQD1 is based on Deere (1963) where break along defects is not considered, and RQD2 is where all the breaks along the defects and laminations are considered. Often during raiseboring, the defects and veins in the rock near the immediate raise wall are dilated and appear as open joints due to low confinement, which then further causes overbreak. Hence, it is imperative to consider the intensity of defects as input for RQD during the assessment. Figure 17 shows the comparison of core conditions related to micro-defects, where the defects dilated after being handled before logging. McCracken & Stacey (1989) recommended Kirsten's (1983) approach to determine SRF. However, Kirsten's approach assumes the maximum principal stress is vertical, which is mainly applied to South African case studies. Peck (2000) developed a method to calculate SRF based on K-ratio and stress-strength ratio, based on Australian case studies, where the SRF factored in a highly horizontal and anisotropic stress condition on jointed rock mass, in which the stress condition is similar to OT's condition.

(a)   (b)
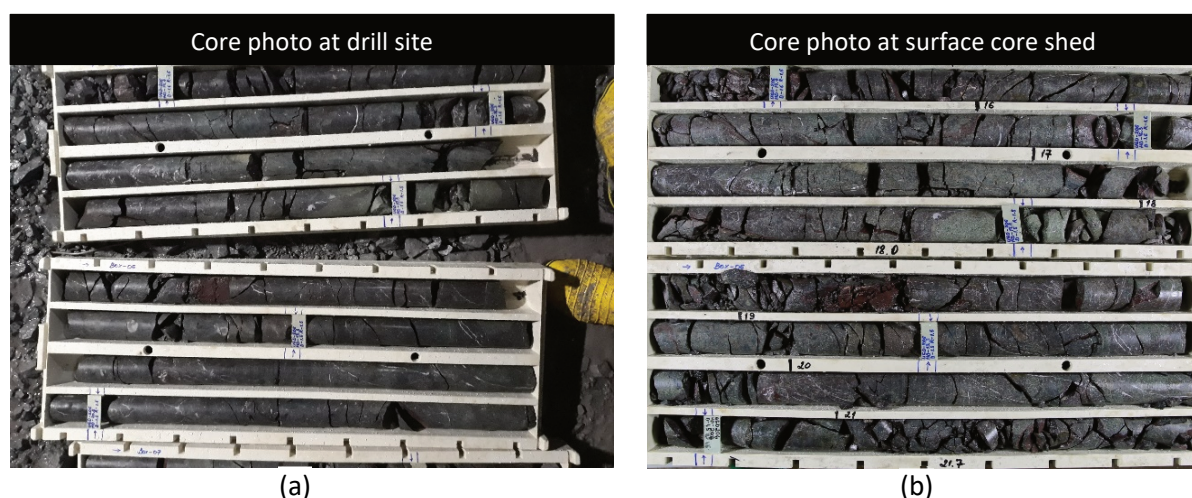
Figure 17 Comparison of core conditions on raisebore investigation diamond drillhole: (a) Core pictured on drill site where micro-defects is still closed; (b) Core pictured at surface core shed during logging, showing dilation of micro-defects and more fractures can be observed easily

5.2   Minimise raise length

Raise length influences the success of raiseboring. The longer the raise length, the degree of rock mass uncertainty increases, which then limits the ability to mitigate the stability risk during the stages of tactical planning and execution. This is due to the longer the raise length, which also increases the exposure time of the raise wall unsupported, which is unfavourable for defected rock mass and high stress conditions. At OT-stress, the raise length design is recommended <40 m, and if the vertical connection is required and the planned raise length is >40 m, a mid-station is then planned to have a series of raises with a length <40 m.

5.3   Plan for the worst-case scenario

Raise-boring at highly defected rock mass and high stress is often challenging, where often geotechnical data cannot be acquired during the life-of-mine design stage and only can be designed with the information available at that time, which data confidence is often low to medium. On contrary, the schedulers and cost estimators required a high level of detail during the planning process. It is often impractical to implement mitigation measures at the tactical planning and execution stages as these mitigation measures will consume the planning contingency, which then increases the risk profile of achieving project milestones and result in significant schedule delay and cost overrun. To counter that, the raises are planned in a worst-case scenario, guided by the risk rating (Section 4) with the assumption that mitigation measures are in place for execution, which also includes the need for geotechnical investigation holes. This planning measure has been successful implemented for OT which has resulted in improvement of schedule and cost compliance, as the result of good collaboration between geotechnical engineers and planners to ensure the raisebore workflow is well understood and properly scheduled.

5.4   Dog-earring and raise overbreak

As the K-ratio (σ_1/σ_3) for vertical raise at production level is 2.15, stress spalling or dog-earing is often observed (Figure 18). The size of overbreak is dependent on the rock mass's intact strength, which is then complicated where the rock is also highly defected. It has been observed that where the rock mass with high veins or defects intensity, the overbreak can be expanded up to 1–2 times the span of the raise diameter at the mid-level of raise, due to the wear impacts during raiseboring. Raises with excessive overbreak will be backfilled with concrete and raisebored again.
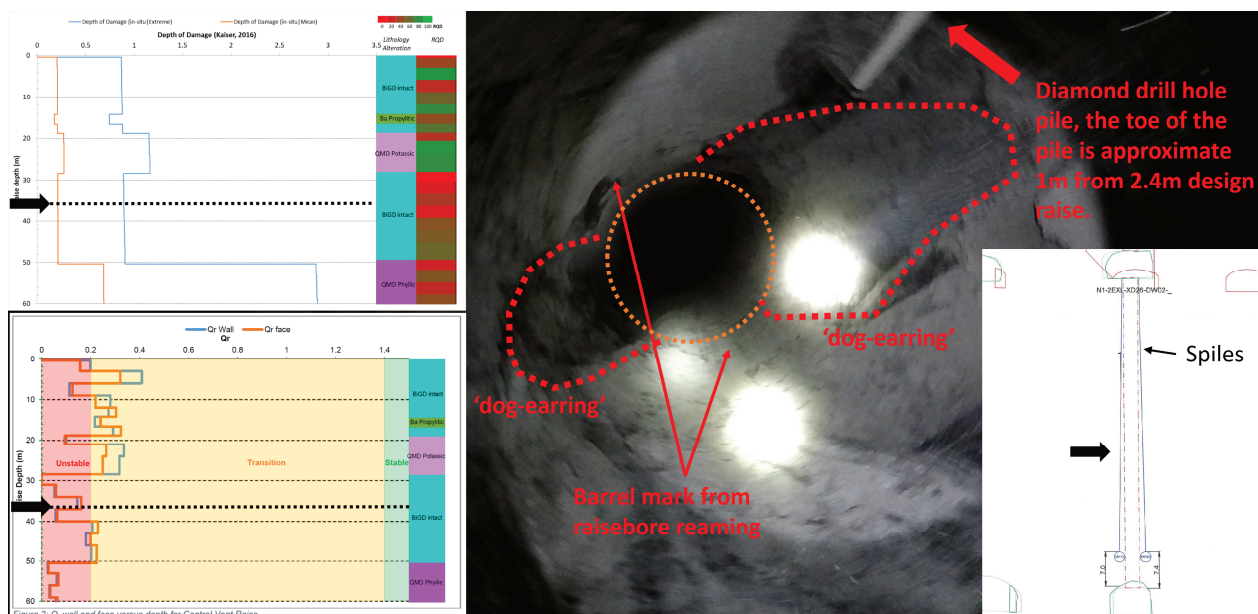
Figure 18   Extends of overbreak on a 60 m raise, where dog-earring is observed. The estimated Qr < 0.1 (left bottom chart) and predicted depth of failure (left top chart) based on Kaiser (2016) is ranged from 0.25–0.9 m

6 Conclusion

Raiseboring at high stress and high defected rock is challenging, and careful design and planning are essential to avoid schedule delays and cost overruns. At OT, a planning and execution workflow is developed, based on empirical methodology, which is simple and easy to use for engineers in different stages of design, planning and execution. Geotechnical investigation holes are important to ensure the stability is properly assessed and mitigation measures are executed. Learnings and observations are recorded systematically in the database and validate the design assumptions and planning workflow. Good collaboration between different teams is imperative to ensure the design and planning objectives are understood and incorporated as design and planning basis.

7 Acknowledgement

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