Optimising for success at the Grasberg Block Cave

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Abstract

At PT Freeport Indonesia's Grasberg mining complex, the Grasberg open pit is scheduled to cease production in early 2019. Mining of the Grasberg deposit will then transition to the underlying Grasberg Block Cave (GBC) mine, with initial undercutting currently planned for late 2018. The GBC is projected to become the district's flagship underground mine for the next two decades.

Early-stage production areas at the GBC are hosted within a heterogeneous rock mass. The footprint will be subjected to variable abutment and cave loading conditions. Mine design and sequencing adjustments, combined with customised ground support options, continually evolve to improve footprint reliability and permit a favourable transition between open pit and underground operations. This paper provides a snapshot of strategies employed to promote the successful caving operation at the GBC mine.

Keywords: *caving, sequencing, ground support*

1 Introduction

PT Freeport Indonesia (PTFI) began the development of the Grasberg Block Cave (GBC) mine with initial access drifting in 2004, fourteen years before the planned initiation of caving in 2018 and almost twenty years prior to achieving full production rates of 160,000 t per day of ore by 2026 (Beard & Brannon 2018). The layout of the GBC, with the overlying Grasberg open pit, is shown in Figure 1.
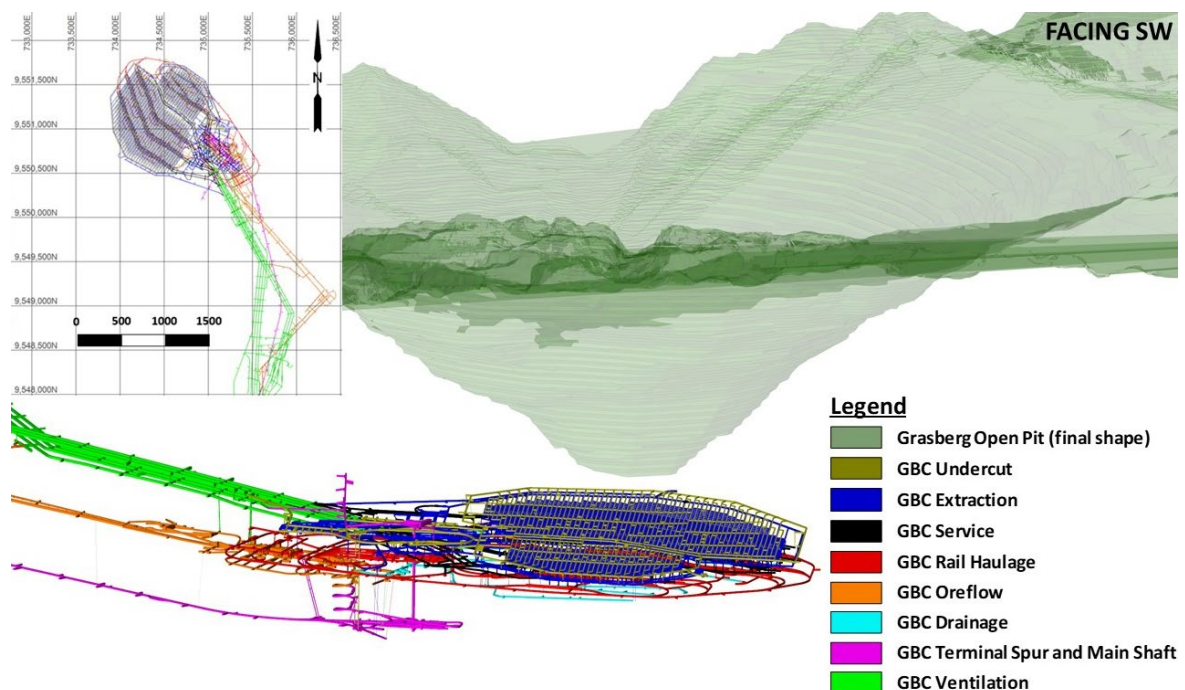

Figure 1   Layout of the GBC footprint and associated infrastructure

The GBC footprint comprises roughly 2,400 drawpoints on a 20 × 30 m drawbell spacing over a 700,000 m^2 El Teniente style layout. The drawpoint opening sequence includes five production blocks, the first two of which are scheduled to be undercut simultaneously in late 2018. Ore will be transported via load–haul–dump units (LHDs) and delivered via loading chutes to a rail haulage system.

Moving from feasibility study through detailed design phases, an improved understanding of footprint geology has necessitated significant modifications to mine design, layout and cave sequencing (Beard & Brannon 2018). Geotechnical assessments have aimed to understand future impacts to footprint stability associated with the strongly heterogeneous rock mass within the GBC. Complex stress paths, variable rock mass conditions and large footprint excavation ratios must be carefully navigated in the coming years to ensure production targets are achieved and maintained.

Preparations taken to improve the reliability of the GBC footprint are outlined in this paper. The continuous cycle of characterisation, analysis and redesign is described herein with attention paid to the integrated efforts of the corporate strategic planning and onsite operations teams. This process is illustrated in Figure 2. Examples of the dynamic, and rapidly evolving design revision process are provided.
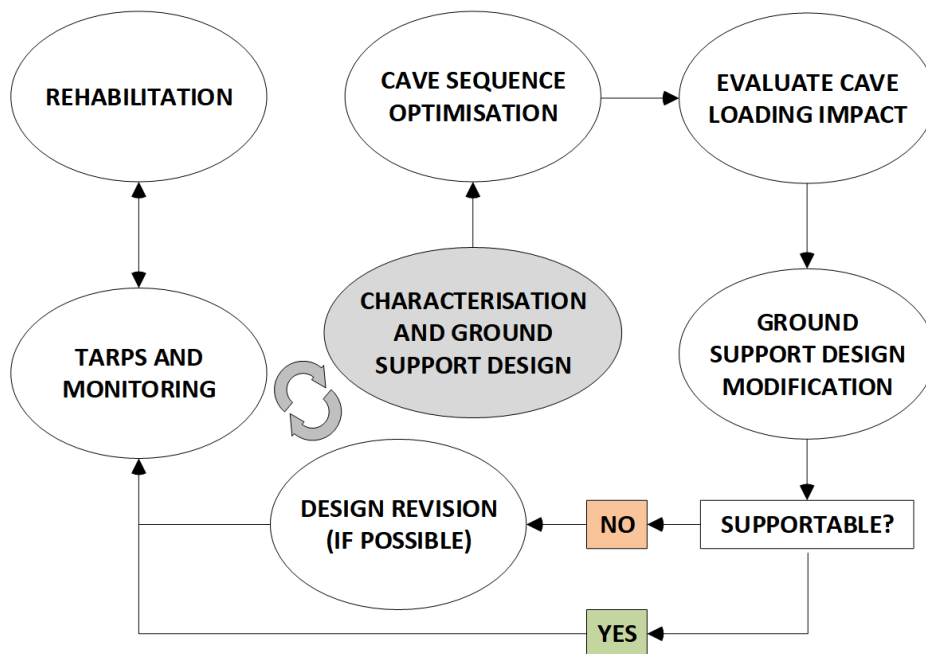

Figure 2   GBC design revision process

2   Geological setting

The Grasberg igneous complex is host to one of the largest known copper and gold porphyry-type ore deposits. The GBC represents the depth extension of the continuous mineralised zone exploited above by the Grasberg open pit. The porphyry copper–gold deposit is comprised of a multistage dioritic intrusion emplaced into the centre of a volcanic breccia complex (Leys et al. 2012).

Geologic units within the GBC are dominated by Tertiary (3.4–3.3 Ma) dioritic to monzonitic intrusions of the Grasberg Intrusive Complex (GIC), which intruded the deformed sedimentary country rocks in a dilational zone associated with strike–slip faulting. The host rock and intrusive units have been subject to multiple episodes of alteration as a result of the emplacement of the GIC and associated hydrothermal fluids. The Grasberg orebody, presently defined as 1% Cu equivalent cutoff, extends from the original 4,200 m surface to currently explored levels below 2,600 m. The late-stage Kali intrusion, which bisects the GBC footprint, is considered barren and is host to extensive infrastructure critical to the success of the mine.

2.1 Rock mass characterisation

Current GBC characterisation includes the following data sources (approximate estimates):

- Geological block model including geological and alteration units.

- Regional and mine-scale fault wireframes.

- 83,400 underground rock mass mapping measurements.

- 624,000 m of geologic and geotechnical drillhole interval logging information from 2,164 drillholes.

- Core photograph database corresponding to the PTFI drillhole database.

- 66,800 point load strength index tests (PLT).

- 400 uniaxial compressive strength tests (UCS).

- 420 triaxial compressive strength tests (TCS).

- 400 Brazilian indirect tensile strength tests (BTS).

Previous investigations (Call & Nicholas, Inc. 2008; PTFI 2016) have demonstrated that geotechnical domains are reasonably well-constrained by the major alteration zones and geological units. These findings have been confirmed by recent face mapping in Production Blocks 1 and 2 (PB1, PB2). As such, geotechnical domains have been spatially established based on a combination of existing geological and alteration wireframes provided by the PTFI geology group.

Figure 3 highlights the currently defined geotechnical domains exhibiting poor–fair rock mass quality within the GBC (based on RMR_{76}). In addition to the wireframes themselves, internal variability in rock mass quality is visible through rock quality designation (RQD) and point load index (PLI) block models (see RQD model in Figure 4). Mean geotechnical parameters for the volumetrically significant domains are provided in Table 1.
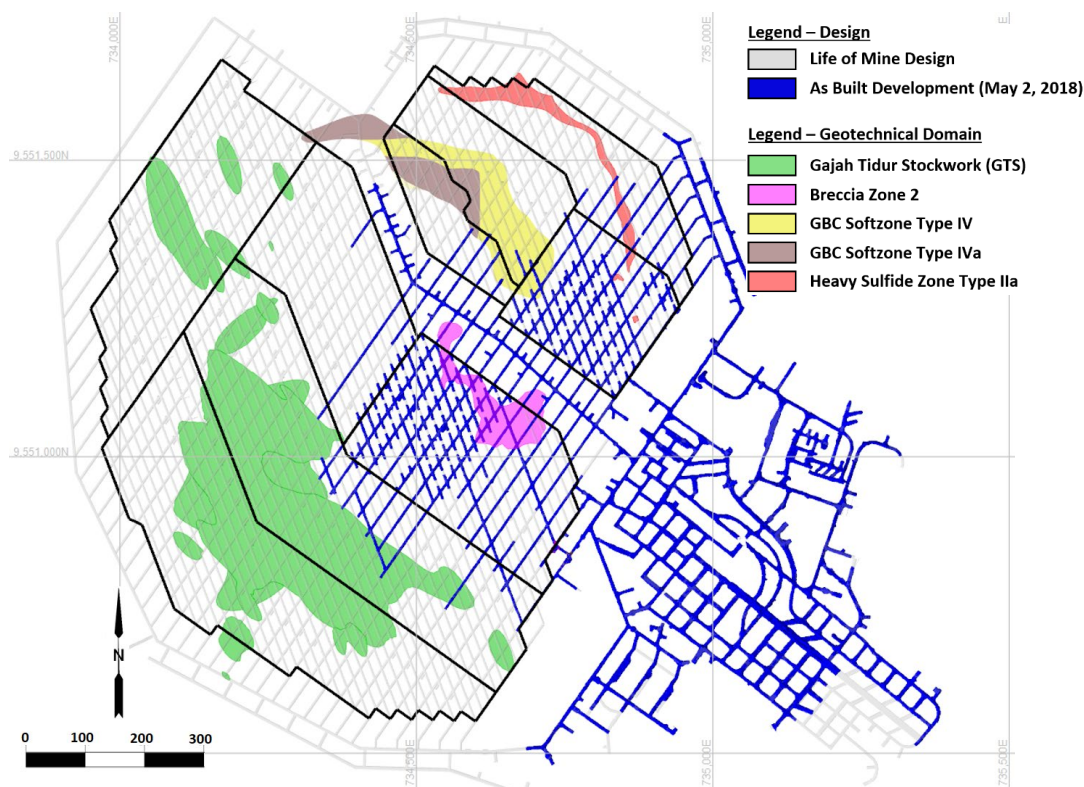

Figure 3   Currently identified geotechnical domains comprised of poor ground on the GBC extraction level footprint (2830L). Note that the Heavy Sulfide Zone (HSZ) and Gajah Tidur Stockwork (GTS) domains are currently being drilled and sub-domained to better constrain areas of poor ground
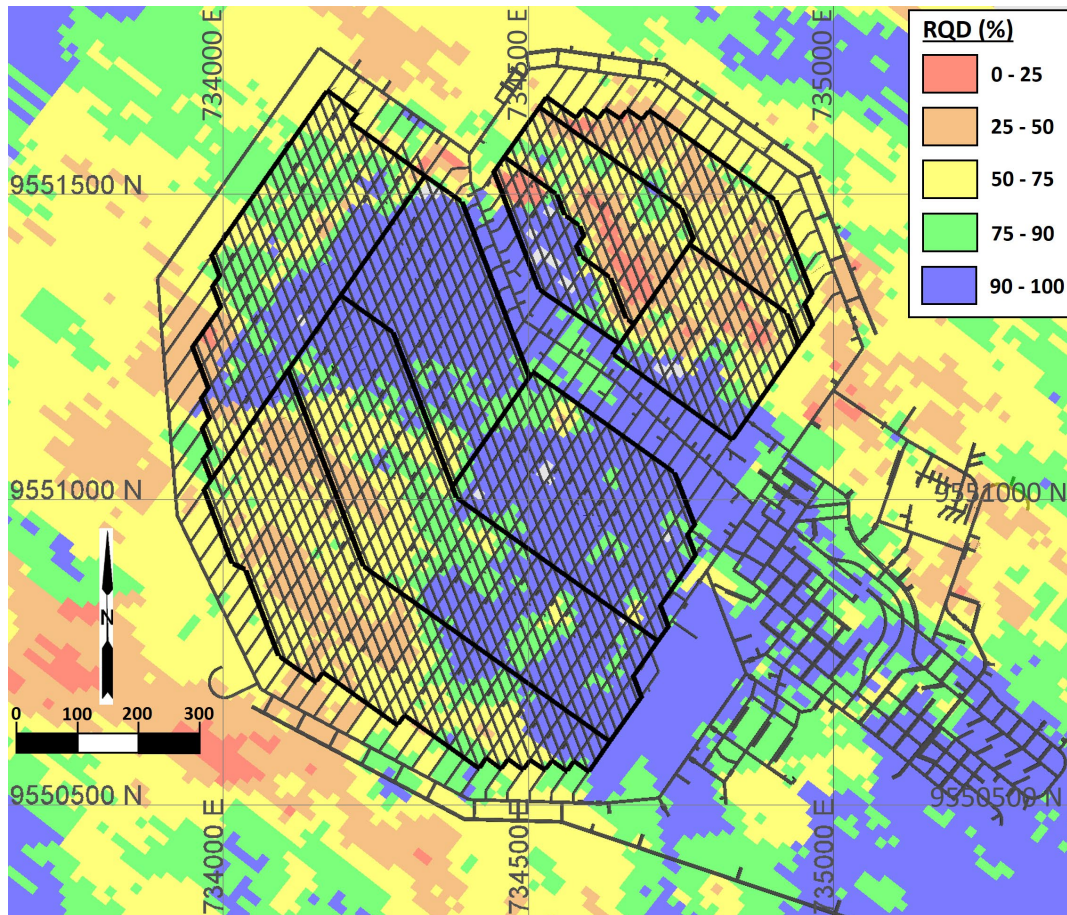
Figure 4   GBC RQD block model cut to the extraction level (2830L)

Table 1   Adjusted median parameters for volumetrically significant GBC geotechnical domains

Geotechnical domain		RQD (%)	FF/m	UCS (MPa)	Ei (GPa)	GSI
Fair to very good ground	Potassic undifferentiated	88	3.7	110	46	70
	Phyllic undifferentiated	85	3.6	95	68	74
	Kali undifferentiated	76	6.0	140	42	68
	Kali sericite–pyrite	72	7.7	100	44	66
	Undesignated sediments	67	7.2	100	53	68
	HSZ	70	6.0	130	96	67
	Sericite–pyrite	74	6.4	80	41	63
Poor to fair ground	HSZ Type IIa	11	16.1	5	5	20
	Softzone Type IV	80	7.0	25	5	55
	Softzone Type IVa	10	16.0	5	5	25
	Breccia Zone 2 (variable quality)	90	4.4	75	44	74
	GTS (variable quality)	70	6.8	80	38	62

Note: FF/m – fracture frequency per metre; UCS – uniaxial compressive strength; Ei – Young's modulus; GSI – Geological Strength Index

The current GBC structural model comprises 25 regional and numerous mine-scale faults. Figure 5 presents the traces of major and mine-scale faults that traverse the footprint. Fault character, which varies throughout the GBC, is routinely incorporated into the design revision process.
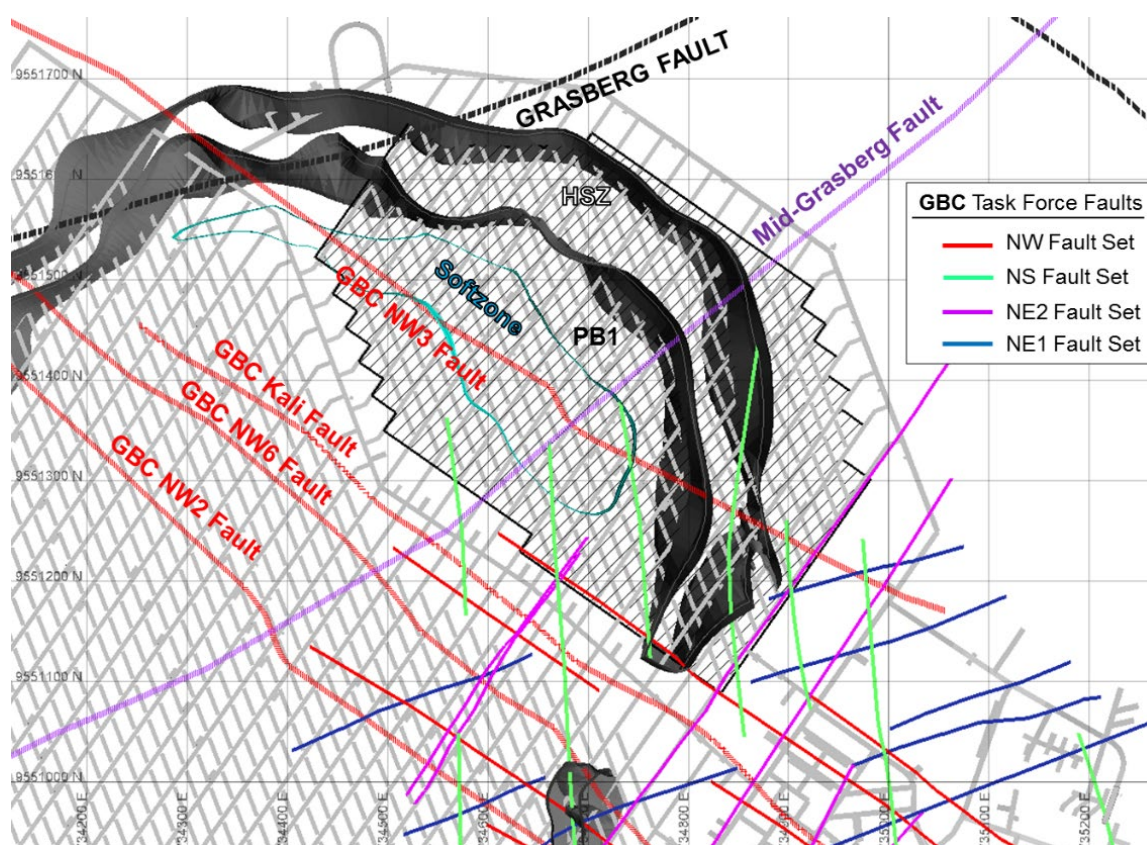

Figure 5   Identified regional and mine-scale faults transecting PB1 and PB2 (2830L)

2.2   Stress

Mine-induced stress is forecasted to vary widely in time and space based on excavation location relative to the evolving cave blocks and the overlying pit. Loading within and adjacent to the footprint will initially spike with the cave abutment, drop sharply, then increase gradually as the cave evolves and breaks through to surface (the pit).

Stress states at each of the defined mining stages are sourced from forward modelling completed by Beck Engineering (2017). Figure 6 presents a generalised representation of the likely stress conditions for each of the main GBC mining stages sampled for a vertical plane through the extraction level (after Golder Associates, 2018). The pre-mining stress state (Stage 0) is in general accordance with the magnitude and orientations of in situ stress data gathered from the 2006 and 2010 field programs (Mining Measurement Services 2010; Ratnaningrum et al. 2016).

Mine-induced stress, combined with rock mass heterogeneity and stiffness contrasts, represents the single most critical factor impacting footprint stability. The following sections describe how the design revision process has considered forecasted stress–strain relationships within the GBC footprint.
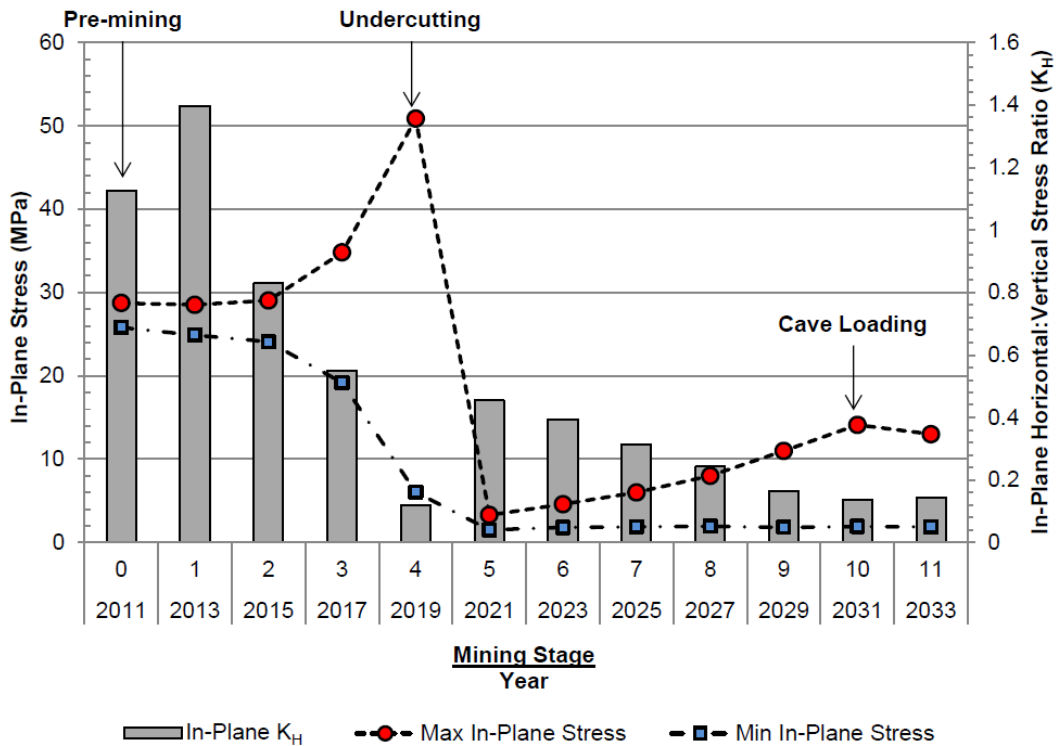
Figure 6   Generalised loading path within the GBC footprint (extraction level; after Beck Engineering 2017; and Golder Associates 2018). The plotted K_H >1 when the major in-plane stress approaches horizontal (<45° from horizontal) and K_H < 1 when the major in-plane stress approaches vertical (>45° from horizontal)

3   Geotechnical considerations for design revision

Undercut and development sequencing is primarily driven by safety and economic factors. Once an optimal sequence is derived, geotechnical risks are defined and communicated back to the mine planning team. Although certain design aspects such as drawpoint spacing, inter-level pillars and footprint areal extents are typically locked in, other aspects can be optimised to reduce geotechnical risk (Beard & Brannon 2018). Together with the PTFI's planning engineers, the following components are typically assessed with each major cave sequence iteration:

- Global footprint stress–strain profile induced by undercutting.

- Fragmentation and caveability profiles per production block.

- Extraction level development sequencing (relative to undercutting).

- Impact to infrastructure below and adjacent to the undercut and extraction levels.

Cave sequence iterations are executed by altering undercut advance and drawbell opening. The GBC sequence, as of Q2 2018, is shown in Figure 7 (after Beard & Brannon 2018). The key geotechnical factors considered with the latest GBC sequence include:

- Global undercut and extraction level stability related to abutment stress in PB1N.

- Kali Corridor stability.

- Design of infrastructure sited in poor ground on the haulage level.

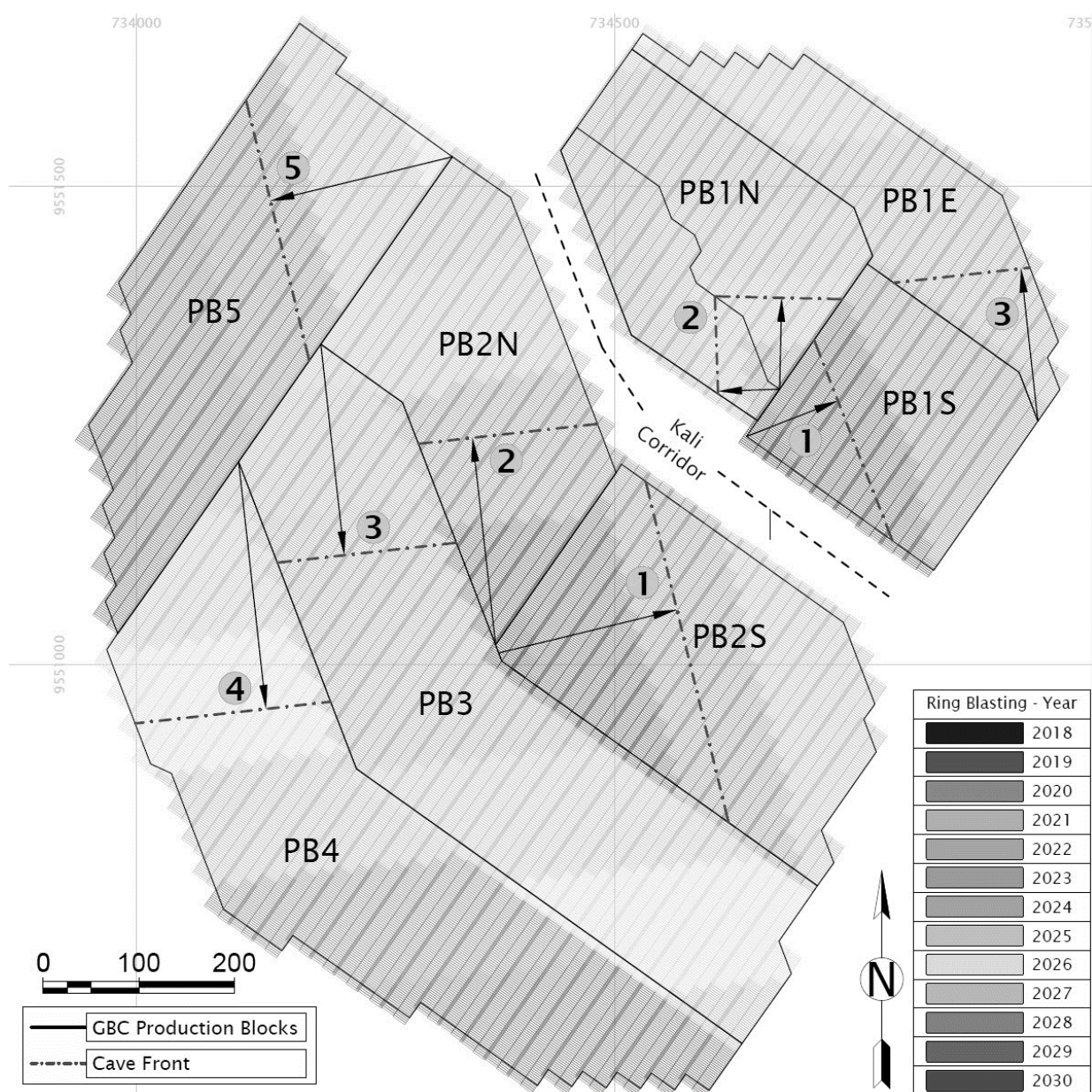- Pit breakthrough location and timing above the GBC.

Figure 7   Current undercut sequencing for GBC life-of-mine (after Beard & Brannon 2018)

The following sections provide examples of how the design revision process is executed in unison with cave and development sequence optimisation.

3.1   Undercut stability in PB1N (2850L)

Numerical analyses suggest that a conventional undercut pattern is unstable within the Softzone domain in PB1N (Beck Engineering 2017; Golder Associates 2016). Given the adverse stress-strength forecasts with the previous PB1N sequence, an alternative undercutting sequence is required. At present, a chevron undercut pattern is proposed for this production block (Figure 7). Although the chevron pattern requires two active undercut faces, modelling results indicate that by transecting the Softzone domain (Figure 3, Table 1) abutment stresses can be better managed. This chevron pattern also improves loading conditions on the services and haulage levels below the extraction level.

In addition to this more favourable advance, non-standard ground support is likely to be required on the undercut (see Section 4).

3.2   Kali Corridor preservation (2850L and 2830L)

The Kali Corridor is a key infrastructure component for the GBC life-of-mine (Figure 7). It provides critical access to development on both the undercut and production levels. The northern section of the Kali Corridor, which includes an arm of the Softzone geotechnical domain, is hosted within a thinner pillar relative to the south section of the corridor. Beck Engineering (2017) illustrated that previous sequences created an adverse loading path which pushed high abutment stresses into the north Kali Corridor (Figure 8).
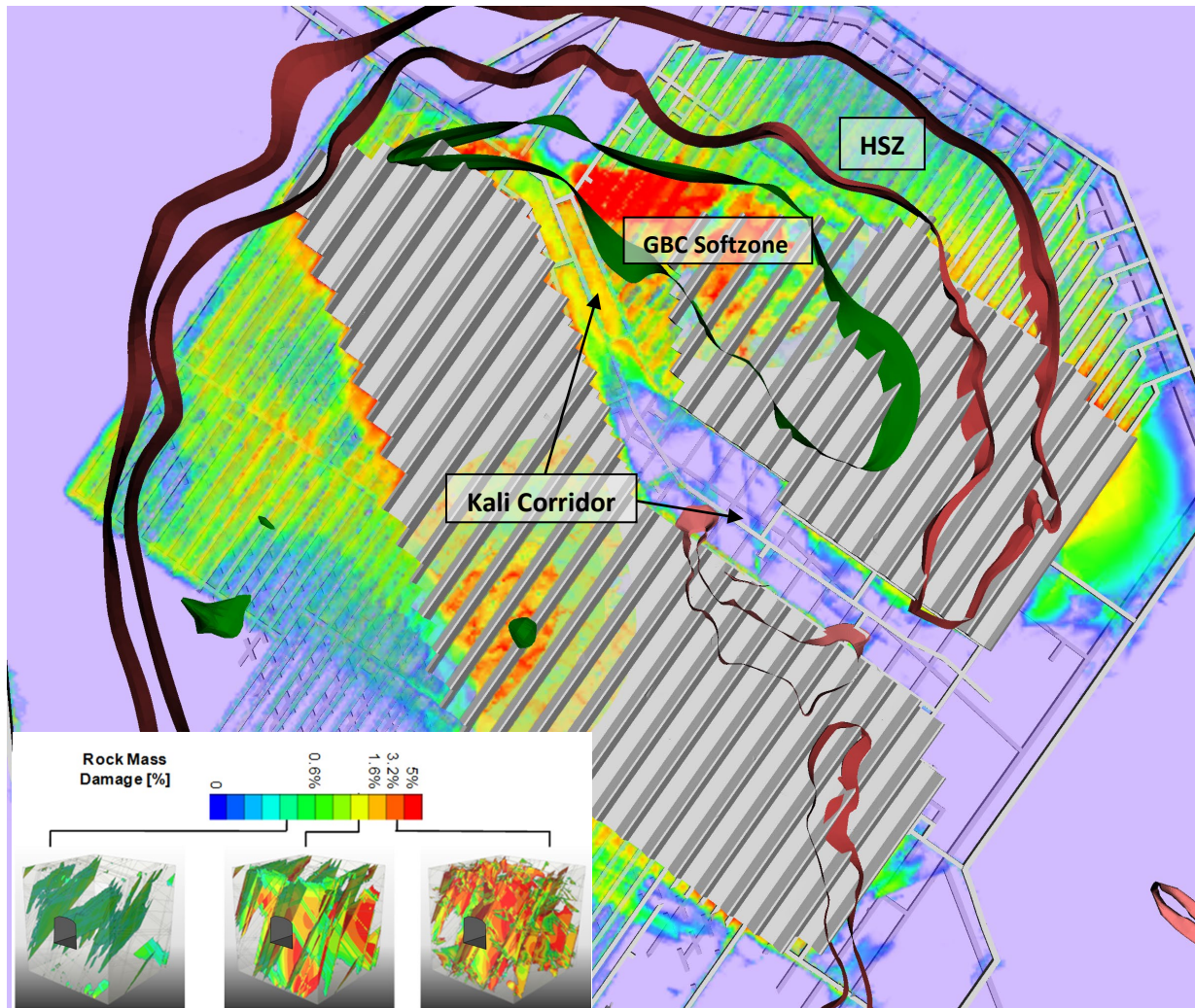

Figure 8   Forecasted strain through 2022 Q4 within the Kali Corridor (after Beck Engineering 2017)

To preserve access to the Kali Corridor, the following steps have been taken through the design revision process:

- Deferment of PB1N and revision of PB2N undercut advance direction.
- Provision to defer a single row of drawbells along the PB2N boundary.
- Review of ground support options within the Softzone on both undercut and extraction levels.

The revised sequence permits early warning for damage onset with the Kali Corridor. Combined with the current sequence, drawbell deferment and heavy customised ground support options aim to increase the reliability of the corridor through its required service life.

3.3   Oreflow system (2760L)

Oreflow infrastructure typically does not permit late-stage design changes due to advance development requirements. Combining extensive metreage with numerous mass excavation needs, the 2760L rail loop is especially difficult to modify at later stages (Pascoe et al. 2016).

However, as geological characterisation is improved and more is learned about ground responses, updates to the design revision cycle are possible, and indeed required. Late-stage geotechnically driven alterations to oreflow system design include the following:

- Reprioritisation of chute gallery and rail loop development based on cave sequencing modifications (per Section 3.1).
- Redesign of chute gallery (CG) designs based on adverse abutment loading.
- Review of ground support and excavation profiles with the main rail track and chute galleries.

Example modifications to the chute galleries include the shifting of CG31 and CG32 locations (Figure 9). The redesign of these facilities was required due to adverse abutment loading forecasts and very poor ground impacting vertical development within the Softzone geotechnical domain. This redesign also affords larger rib pillars between the chute galleries and associated main rail track. Although this redesign did not mitigate all identified geotechnical risks (e.g. adverse geological contacts), it is the opinion of the authors that the reliability of the new design will outperform the previous iteration.
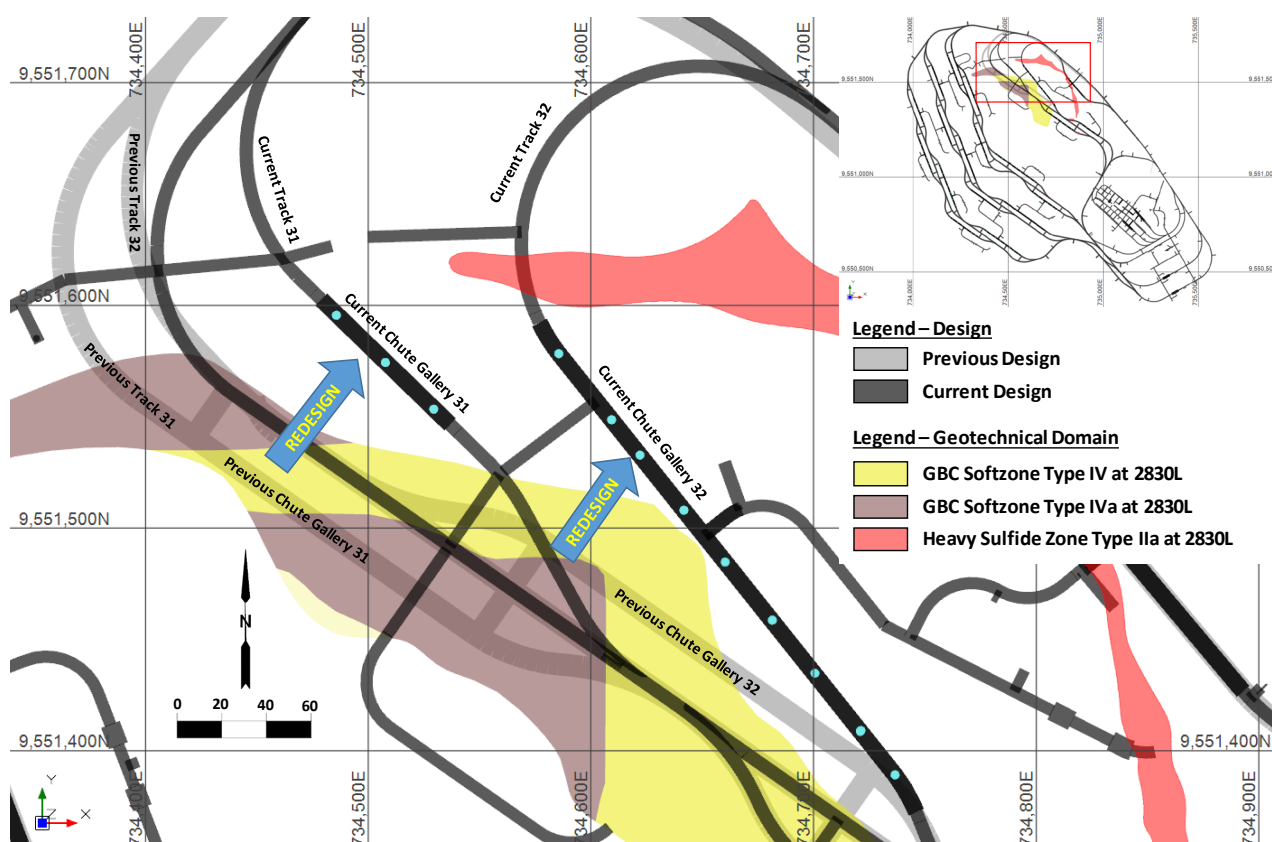

Figure 9   CG31 and CG32 original and redesign (with 2830L Softzone and HSZ Type IIa domains)

On a more local scale, the main rail tracks have been modified through the design revision process where geotechnical risk has been identified. To manage stresses related to abutment and cave loading, a selection of main rail track segments have been redesigned to include inverted floors and floor bolting (inverted floor profile shown in Figure 10). Where the design revision process is insufficient to fully mitigate damage, monitoring and rehabilitation, managed through trigger action response plans (TARPs), is considered the most appropriate risk management tool.
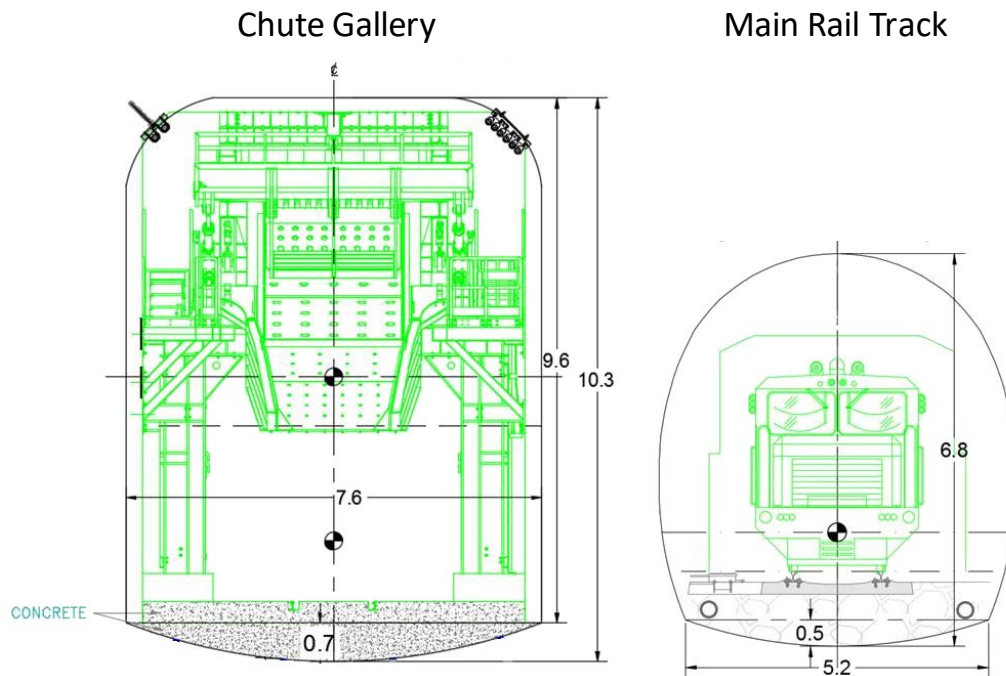
Chute Gallery   Main Rail Track

Figure 10 Inverted floors added to risk-prone segments of chute galleries and main rail track (dimensions in metres)

4   Footprint ground support

Ground support installed within the GBC footprint is designed to provide a safe production environment during the undercutting process and subsequent cave production. These support systems will be relied upon for the life of the excavation.

Beck Engineering (2017) performed a series of simulations looking at the performance of the extraction level and undercut given the current cave sequence. From these simulations, a stress tensor database was developed, and used as inputs into standard and non-standard (customised) ground support designs.

The main drivers on ground support demand are undercutting sequence, development geometry and development layouts. Depending on the design and sequence selected, support system demands can be reduced based on observed performance. The following aspects, at a minimum, must be addressed prior to developing support systems within the GBC:

- Undercut method (pre, advance, or post).

- Undercut advance rate.

- Extraction level layout (pillar sizes and shapes).

- Undercut lead-lags.

- Separation distance between undercut and extraction level.

- Geology and structure.

- In-panel facilities (grizzly, rock breaker stations, ventilation raises, etc.).

GBC ground support is designed to control the rock mass following initial failure, in which deformation management is key. Deformation management is utilised in excavations where stresses generated in the excavations cannot practically be overcome by reinforcing the ground with support. The main goal with deformation management is to provide a system that can keep the excavation safe while still withstanding the estimated closures. In addition, the system should allow for quick rehabilitation when closures become an operational problem.

4.1 Standard ground support

The standard ground support designs for the GBC footprint are based on a maximum in-plane stress of 32 MPa, oriented nearly vertical, and a minimum in-plane stress of 24 MPa, oriented nearly horizontal. Fair–good and poor categories are defined based on typical rock mass quality and loading scenarios. Considering the rotation of the in-plane stresses from horizontal to vertical as cave abutment and production phases occur, the ground support systems must consider both high horizontal and vertical stress as well as a post-abutment unloading phase throughout the life-of-mine.

Although each design is evaluated on a case-by-case basis through a multistage approval process, standard ground support designs have been established to cover typically encountered conditions. Given the extensive range of development geometries and ground conditions, 40 support standards exist for the GBC.

4.2 Non-standard ground support

For abnormal excavations or very poor ground conditions, non-standard ground support designs are required. The most notable example of non-standard ground support is currently being applied to the Softzone geotechnical domain within PB1 (Figure 3).

It is forecasted that the Softzone domain will suffer from excessive strain under cave abutment and cave loads, which will lead to high levels of deformation and squeezing ground. To mitigate this risk, a steel, rebar and concrete liner system has been designed by Golder Associates (Figure 11, Golder Associates 2018). This system is currently being installed through a well-monitored trial within Panel 26 of PB1.
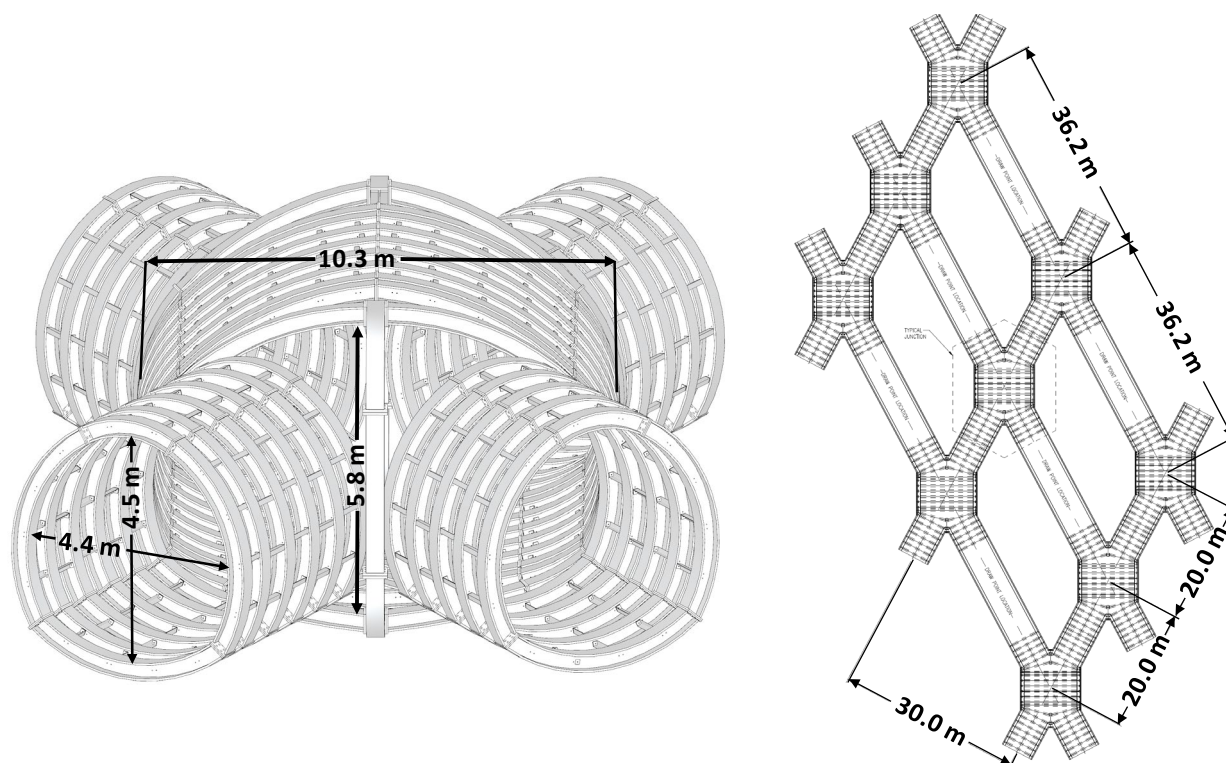

Figure 11   Steel–concrete liner developed for the GBC extraction level panel drives within the Softzone geotechnical domain (after Golder Associates 2018); isoview (left), plan view (right)

The Panel 26 liner trial will allow PTFI to gather data on the performance of the liner system as PB1 South is mined (Figure 7). Construction experience will also be gained with installation in the event that the system is implemented on a larger scale within the Softzone domain. Results from the trial ultimately drive future requirements of the liner system while permitting a better understanding of potential schedule and metal delays. In the meantime, alternative mining strategies and support design are being assessed for PB1 North.

5   Hazard readiness and response

Cases exist in the GBC where steps in the design revision process cannot be accommodated. In such cases, monitoring and rehabilitation schedules are developed and modified based on forecasted excavation and ground support performance.

The GBC standard and non-standard support designs have certain functional capacity limits. It is the responsibility of the site team to develop a series of TARPs for each support type so that rehabilitation can occur prior to the support system reaching its maximum capacity. TARPs will have to be developed on a support system basis, but as a rule, the following are signs that something is happening to the support system and should be investigated:

- Excessive shotcrete cracking and mesh bagging.

- Rebar or cable bolt plates being pulled through, bent or pig-tailed (cable bolt ends).

- Excessive drive deformation (observed through convergence monitoring, and scanning).

- Signs of brittle failure (spalling, rock noise, strainburst).

- Corrosion.

Accordingly, the following TARP objectives are defined:

- Manage risk to mine personnel and equipment related to excavation stability hazards during development and construction activities.

- Achieve early identification of excavation displacements.

- Develop action plans related to access restrictions, proactive support maintenance (PSM) and more extensive campaigns of rehabilitation.

A geotechnical hazard map (GHM) is being developed which will aid in the forecasting of rehabilitation and PSM related to support consumption through displacement and corrosion. The GHM will also help to differentiate areas of varying hazard in general terms from a ground condition and stress loading perspective. The GHM will be maintained in a centralised spatial database thus allowing multiple teams to gain access for forward planning purposes.

6   Conclusion

It is the aim of the PTFI geotechnical, engineering and operations teams to create conditions which promote the success of the GBC footprint as the mine moves into production. When combining an aggressive GBC ramp-up schedule with a highly heterogeneous rock mass subjected to complex loading cycles, the design revision cycle has been challenged. In several instances, global and local-scale redesign has been undertaken in short order to optimise footprint reliability. Where redesign is not an option, aggressive ground support solutions have been developed. TARPs, coupled with timely support maintenance and rehabilitation, will allow mine operations to effectively focus on maintaining reliability of critical footprint excavations. Where required, redundancy has been worked into the mine plan to reduce the impact of repair periods on production.

Acknowledgement

References

Beck Engineering 2017, *GBC Cave Simulation*, report submitted to PT Freeport Indonesia, Beck Engineering, Sydney.

Beard, D & Brannon, C 2018, 'Grasberg Block Cave mine: cave planning and undercut sequencing', in Y Potvin & J Jakubec (eds), *Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth. pp. 373–384.

Call & Nicholas, Inc. 2008, *GBC Geotechnical Feasibility Study*, report prepared for PT Freeport Indonesia, Call & Nichols, Inc., Tucson.

Golder Associates 2016, *3D Numerical Stress Modelling and Ground Support Assessments of Extraction Level Excavations in the "Weak" Zones of Production Block 1 at the GBC*, report submitted to PT Freeport Indonesia, Golder Associates.

Golder Associates 2018, *Panel 26 Liner Design*, report submitted to PT Freeport Indonesia, Golder Associates.

Leys, CA, Cloos, M, New, B & MacDonald, GD 2012, 'Copper-gold-molybdenum deposits of the Ertsberg-Grasberg District, Papua, Indonesia', in JW Hedenquist, M Harris & F Camus (eds), *Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe, Special Publication 16*, Society of Economic Geologists Inc., Littleton, pp. 215–235.

Mining Measurement Services 2010, *GBC Mining Area: Rock Stress Measurements*, report issued to PT Freeport Indonesia, Mining Measurement Services, Macclesfield.

Pascoe, ND, Mead, B & Vega, H 2016, 'Grasberg Block Cave haulage project – design and construction update', *Proceedings of MassMin 2016*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 585–598.

PTFI 2016, *Rock Mass Characterization for GBC PB1*, internal PT Freeport Indonesia report, PT Freeport Indonesia.

Ratnaningrum, A, Yudanto, W, Wilson, AD, Purwanto, H & Litterbach, J 2012, 'In situ stress measurement and interpretation at the Grasberg Block Cave mine, PT Freeport Indonesia', *Proceedings of MassMin 2012*, The Australasian Institute of Mining and Metallurgy, Melbourne.