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Brow set design background and practical learnings from Panel 0 block at Oyu Tolgoi underground mine

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Abstract

Drawpoint stability and reliability are critical for caving mining productivity, and brow sets are one of the critical support elements dictating drawpoint production life. This paper outlines the design philosophy, installation approach and current performance of brow steel sets at the Oyu Tolgoi underground mine.

The Hugo North orebody at Oyu Tolgoi contains several major geological structures within the Panel 0 caving footprint, and some drawpoints are located within fault zones. These faults and poor ground conditions adversely affect the rock brow stability and often lead to early brow erosion. To mitigate these risks, pre-consolidation measures and brow set repair strategies have been incorporated into this study.

Determining the demand for brow sets during the study stage is challenging due to operational uncertainties. The selection of brow steel sets depends on expected ground conditions and anticipated reserve tonnage or production life span. Benchmarking brow erosion from other block caving operations was also used to determine the appropriate rock brow distance to the brow set.

The initial concept design comparisons for brow sets included the following options:

- *flat-back brow sets with top beam*
- *full-arched, heavy-duty steel brow sets*
- *two- or four-legged brow set configurations*
- *a rationale behind these design choices for Panel 0 at Oyu Tolgoi that considered both operational requirements and practical constraints.*

Keywords: *steel brow set, deep caving mine, heavy-duty steel set, drawpoint stability, brow wear, brow erosion*

1 Introduction

The Oyu Tolgoi mine is located in Umnugovi Province, within the South Gobi region of Mongolia. The site is approximately 550 km south of the capital city, Ulaanbaatar, and about 105 km north of the Mongolian–Chinese border. The Oyu Tolgoi mineral deposits comprise Hugo North, Hugo South, Oyut and Heruga, where economically significant mineral resources have been identified. The weak, massive nature of the orebody, with its depth below surface, makes it well suited both geotechnically and economically for the block caving underground mining method. The first underground production mining area is Hugo North, where two mining lifts are planned. The first lift, Hugo North Lift 1 (HNL1), consists of four blocks: Panel 0 (P0), Panel 1 (P1), Panel 2 north (P2N) and Panel 2 south (P2S). Currently, production from the P0 block is ongoing, while undercutting for the P2N and lateral development of P2S is in progress. The Oyu Tolgoi mine is geologically complex and contains several major fault structures, with extremely poor ground conditions (Figure 1). The P0 block caving mine has an El Teniente extraction layout and advanced undercutting method. The P0 footprint measures approximately 260 × 320 m and consists of 229 drawpoints.

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This paper primarily focuses on the background of brow set design, the evolution of the design and underground installation practices, observed damage during P0 block-caving operations and an overview of preventive measures proposed for the P2N block.

In the terminology for a block caving mine, the brow refers to the overhanging, often unsupported, near-vertical face formed at the intersection of vertical or sub-vertical and horizontal excavations, such as the interface between a drawpoint and a drawbell. A brow set is defined as a steel support assembly installed to stabilise and support the brow of a drawpoint (van As 2010). The primary functions of brow sets are outlined as follows:

- Provide load-bearing capacity to carry partial column loads, and confinement to the brow rock mass.
- Mitigate blasting-induced damage to the rock mass.
- Maintain brow stability to create safe and continuous access for ore extraction activities, including mucking and secondary breakage.
- Act as a flow regulator to control caved material rilling into extraction-level drives.
- Provide resistance to brow wear, thereby prolonging the productive life span of drawpoints.
- Serve as a visual indicator of brow location, reducing personnel exposure to rockfalls and sudden solid or fine material inrush (Talu & Ooi 2018).

Brow sets are not designed as ground support elements to withstand deformation and convergence due to cave loads. The stiff brow set primary function is to provide brow stability by supporting dead weight from cave loading and maintaining longer-term access to the drawpoint. It should be noted that the secondary function of a stiff brow set is to provide passive ground support to the drawpoint. However, this should be viewed as an addition to current designed ground support, which provide active pressure on the surrounding rock mass (Ooi & Watt 2020).

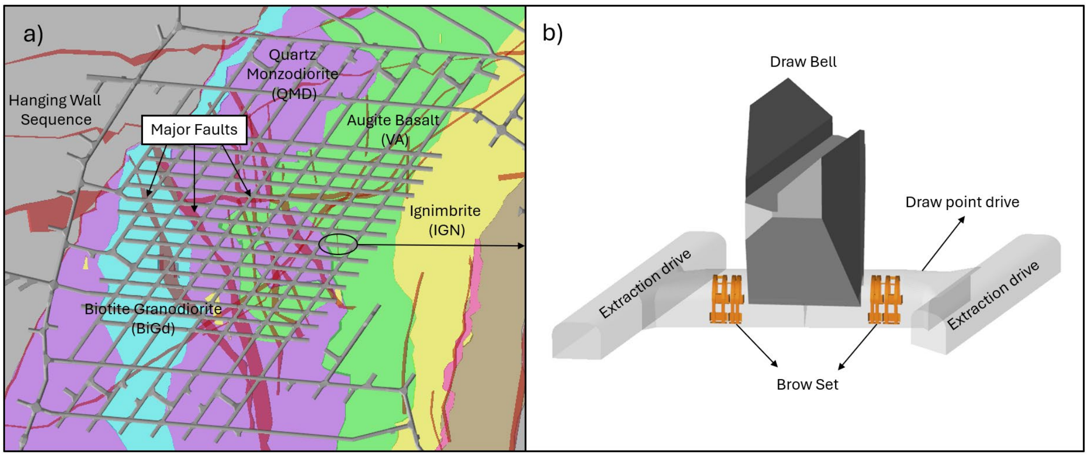


Figure 1 (a) Geological map and Panel 0 extraction layout; (b) Brow set location for extraction drive

2 Brow set design background

2.1 Initial design options

There is no universally accepted industry standard for the design of brow sets. Consequently, brow set design is typically based on rock engineering principles, benchmarking, operational experience and site-specific observations. Determining the demand of the brow set design is based on the following:

- production life of drawpoints/anticipated reserves and height of the draw
- ground conditions of the drawpoints/potential of brow erosion or wear risks.

The production modelling for Oyu Tolgoi P0 block indicates that most of the drawpoints will experience 250–400 kt reserves and a 350–500 m height of draw, not considering the early drawpoint closures. So production life of the drawpoints will be around 5–10 years.

In terms of rock mass conditions, the Oyu Tolgoi P0 block sits within several lithology contacts and major faults. Those drawpoints located within the major structures will be exposed to very poor rock mass conditions (Mining Rock Mass Rating < 30), as shown in Figure 1. The nature of a porphyry deposit is that with the geological faults and structures, this is usually where the mineral resources are located. Therefore, those drawpoints in the weak ground conditions result in the highest ore value. Considering these assumptions, heavy-duty steel brow sets were justified and, during the initial design stage, three design options were evaluated (Figure 2):

- flat-back steel brow sets with top beam
- full-arched heavy-duty steel brow sets
- two-legged or four-legged brow set configurations.

The main advantages of the flat-back steel set are ease of production and a smaller envelope, leading to lower cost and easier installation underground. During the initial design stage in 2018 it was found that most caving mines used flat-back brow sets.

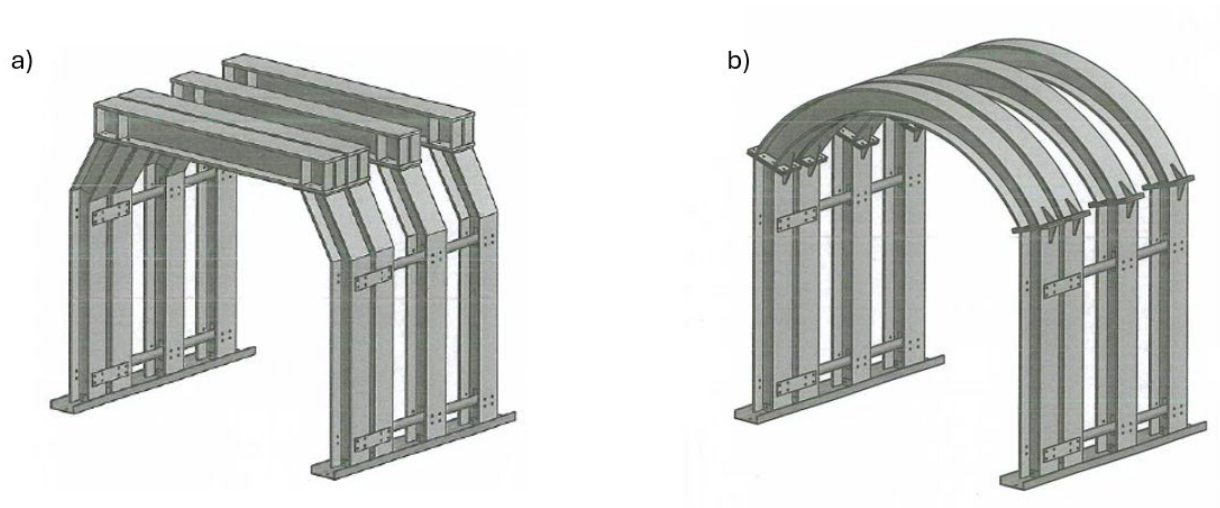


Figure 2 (a) Flat-back steel brow sets with top beam; (b) Fully arched steel brow sets

As higher demand is anticipated at the drawbell side due to brow wear and erosion risks, the spacing between the two legs on the drawpoint side was reduced to increase resistance capacity against brow wear. A two-leg set option was also considered during the initial design stage for good ground conditions, where rock erosion rates are low and the surrounding rock mass is competent. However, during the execution stage, all drawpoints were constructed using four-leg brow sets, considering uncertainties during production. Factors such as hang-ups and slow draw rates could lead to compaction of the muck pile.

2.2 Capacity calculations

The anticipated predominant loading condition for the P0 drawpoint is vertical column loading, as advanced undercutting is used in P0. Wilshaw Engineering conducted the capacity calculations and prepared the detailed drawings for Rio Tinto in 2013. A Space Gass model was used to determine the load-carrying capacity under both horizontal and vertical loading conditions for all design options (an example of which is shown in Figure 3).

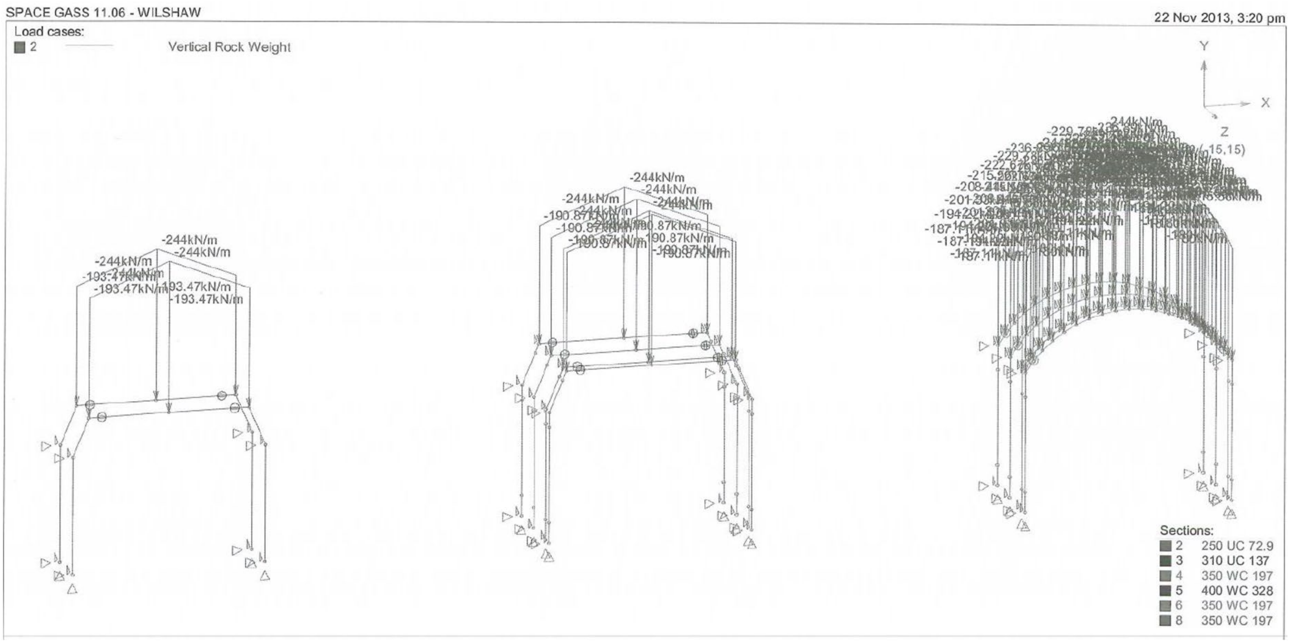


Figure 3 Space Gass 11.06 modelling output (Edmands & Rasmussen 2013)

The capacity calculation results indicated that the four-leg flat-back brow set was more than three times stronger than the two-leg flat-back brow set. In addition, the arched brow set demonstrated up to 20% higher capacity compared to the flat-back brow set (Table 1). Overall, the arched brow set showed the highest load-carrying capacity among the design options assessed.

Table 1 Space Gass modelling output comparison for the three design options

Types of sets	Element	Section name	Yield strength (MPa)	Total length (m)	Segment length (m)	Failure mode	Load factor
Flat-back brow set with 2 legs	Vertical legs	250 Universal Column (UC) 72.9	235	3.35	3.35	Shear	1
	Horizontal top beam	310 UC 137	235	3.369	3.369	Member	0.94
Flat-back brow set with 4 legs	Vertical legs	400 Wide Flange Column (WC) 328	280	3.542	3.542	Member	3.07
	Horizontal top Beam	350 WC 197	280	3.68	3.68	Shear	3.07
Arch steel brow set with 4 legs	Top arch	350 WC 197	280	5.108	5.108	Shear	3.37
		350 WC 197	280	5.108	5.108	Member	3.7
	Vertical legs	350 WC 197	280	2.953	2.953	Shear	3.61
		350 WC 197	280	2.953	2.953	Member	3.7

2.3 Benchmarking of other caving operations

During the 2018 brow set design stage, most caving operations implemented flat-back brow sets, with the exception of a few Chilean caving mines. A common failure mechanism observed for these brow sets was failure of the flat-back beam. Figure 4 illustrates rapid brow set damage at the Argyle diamond mine in

Western Australia, which occurred within a three-month period. At that time, the mine was using a two-leg flat-back brow set.

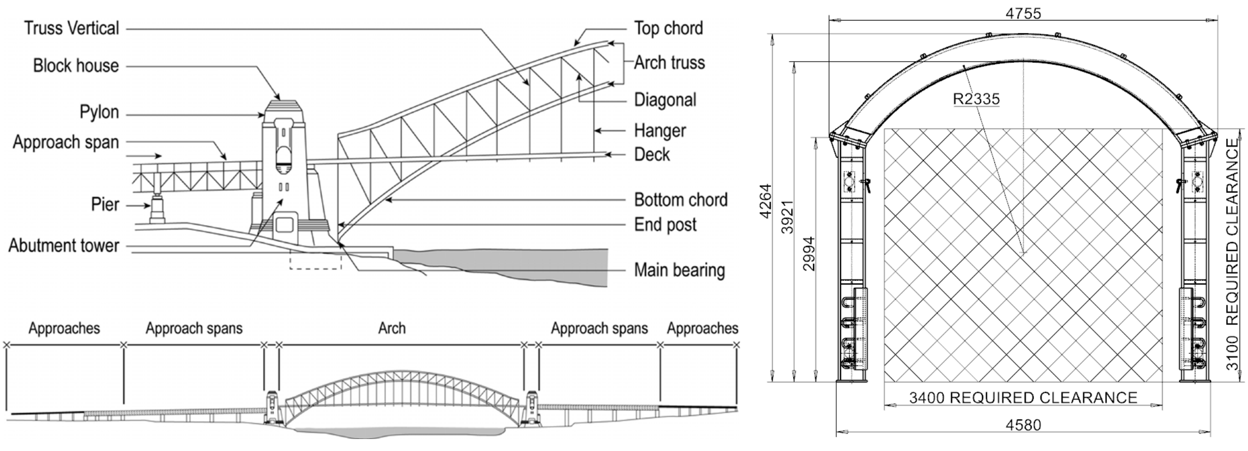
Figure 4 Rapid brow set damage after three months at Argyle diamond mine

Additionally, benchmarking was undertaken to inform rock brow sizing. Available information from other mining operations indicated that average rock brow erosion in high-tonnage drawpoints (> 180 kt) was approximately 0.6 m in good ground conditions and could exceed 1.0 m in poorer ground conditions. Most of this erosion occurs early in the draw life of a drawpoint and progressively decreases over time as a natural chamfer develops on the rock brow (Ooi & Watt 2020). Based on these findings, a 1.0 m rock brow was adopted in the design for the Oyu Tolgoi underground mine.

The steel arch concept is widely applied in civil and structural engineering, particularly in the design of large-span bridges, where vertical loads are redistributed through arching action to the abutments (refer to Figure 5b). When applied to brow set design, the primary advantage is that the arched top member enables high column loads to be redistributed toward the vertical legs of the brow set, which represent the highest-capacity elements under vertical loading conditions (Table 1). These loads are subsequently transferred into the surrounding rock mass. This load redistribution mechanism reduces localised stress concentrations and enhances overall structural performance under predominant vertical loading conditions.

2.4 Internal clearance and selection of the brow set

In addition to geotechnical considerations, brow set design is constrained by several operational requirements. These include internal clearance requirements for load–haul–dump equipment. A 14 tonne loader was planned for use at Oyu Tolgoi, which requires a minimum internal clearance of 3,400 mm for the brow sets (Figure 5b).



(a) (b)

Figure 5 (a) Sydney Harbour Bridge drawing (Godden Mackay Logan Pty Ltd 2007); (b) The original brow set drawing for Oyu Tolgoi

Considering the outcomes of structural capacity assessments, failure observations from other mining operations, and the anticipated drawpoint production life and ground conditions, a full-arched heavy-duty steel brow set was selected for the Oyu Tolgoi underground mine brow set design (Figure 5, right).

3 Evolution of design and installation approaches

3.1 Design evolution

After completion of the brow-set design selection, an installation and assembly trial was conducted under the surface facility. (Figure 6a) The primary challenge identified during this trial was the installation of the top arched section. The width of the original arched section was 4,755 mm, while the main extraction drive width is 4,500 mm and the drawpoint drive width is 5,100 mm. As a result, transporting and installing the long top arch underground was time-consuming and not well-suited to rapid underground development.

To address this issue, design modifications were implemented without compromising the full load-bearing capacity of the brow set, as shown in Figure 6d. The length of the top arch brow set was reduced to 3,755 mm and the vertical beam was extended to form an enhanced shoulder section (Figure 6c) This revised configuration significantly improved the ease of underground installation of the top arch. To date, no failures have been observed in the shoulder areas where the joints are located. Additionally, four 2.4 m resin bolts are installed at each side of brow set to prevent the legs being kicked off the concrete foundations.

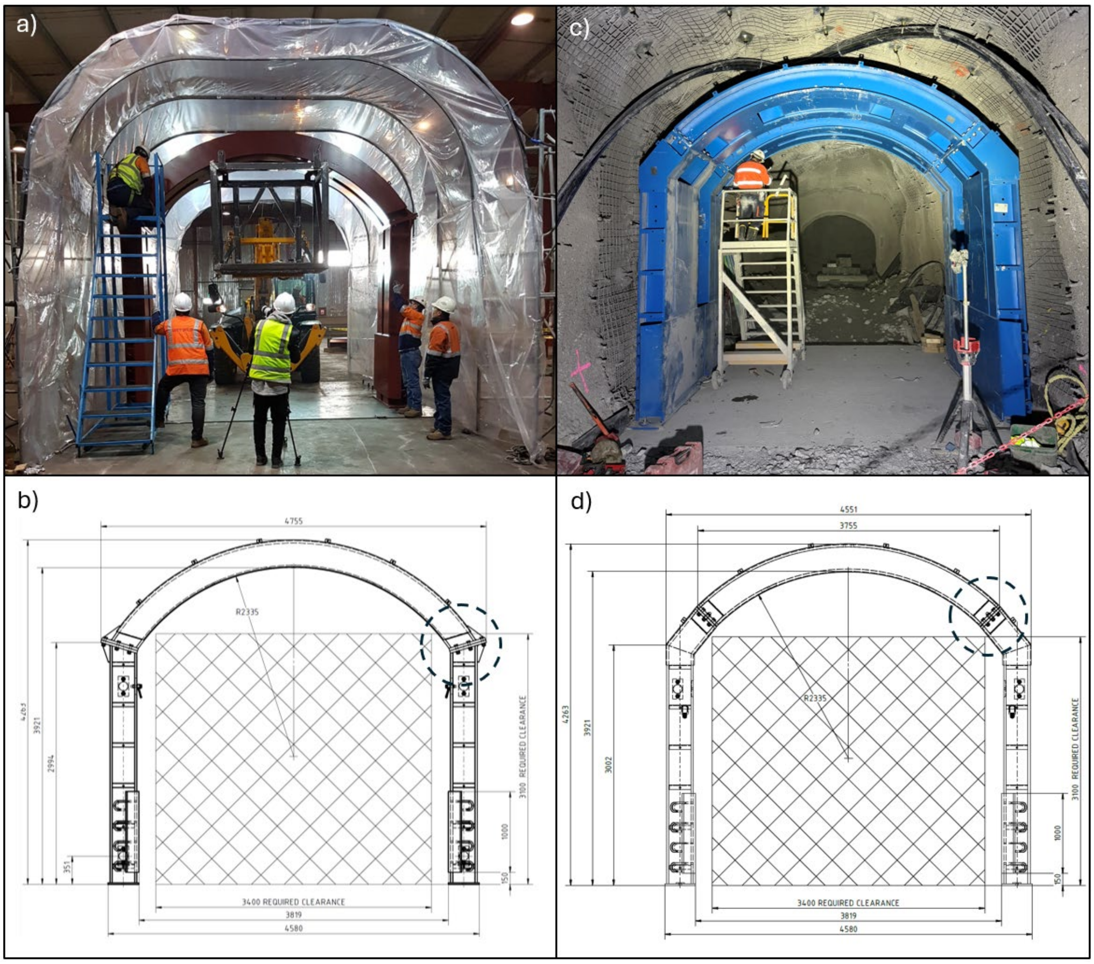


Figure 6 (a) Original brow set installation trial and (b) original brow set drawing (c) Installation of modified brow set underground and (d) modified brow set drawings (ZM Engineering 2025)

Further modifications have been made to the design up to the current stage to improve the effectiveness of concrete infill and connection points. The design also incorporates a steel mesh to reinforce the poured concrete, as shown in Figure 7.

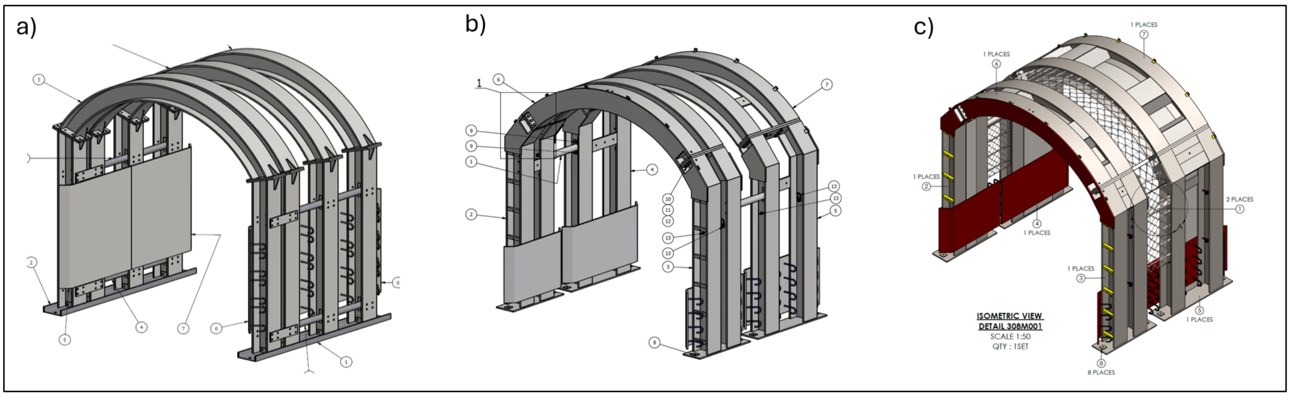


Figure 7 (a) Original brow set design; (b) Modified design with reduced arch; (c) Current design

The original sequences of underground brow set installation were:

1. Pour blinding concrete to provide a flat, level pad.
2. Mark out a template for hold down bolt locations and then install rockbolts (Figure 8a).
3. Lift the column set using a Rud load ring and two legs slung from horizontal to vertical and install over the rockbolts (Figure 8b).
4. Install the arched beam sets using a lifting jig, align it with guide pins and bolt it to the column.
5. Install the remaining third and fourth column sets with rockbolts.
6. Install the arched beam set and bolts to the column (Figure 8c).
7. Pour a 200 to 300 mm-thick concrete slab.
8. Fix temporary formwork against columns and scribe off to the wall.
9. Pour sidewall concrete to completely encase the column on both sides.
10. Install an arch-formwork shutter onto the jacking frame outside of the brow set and pour concrete to completely encase the entire brow set (Wilshaw Engineering 2021a).

The installation sequence of the brow set for P2N is further changed to accelerate the installation time. The main changes were the spraying of shotcrete at connection points where wire mesh is installed and pumping concrete to fill the brow set entirely using pre-installed poly pipe. This modification reduces the formworks and sequential concrete pouring time.

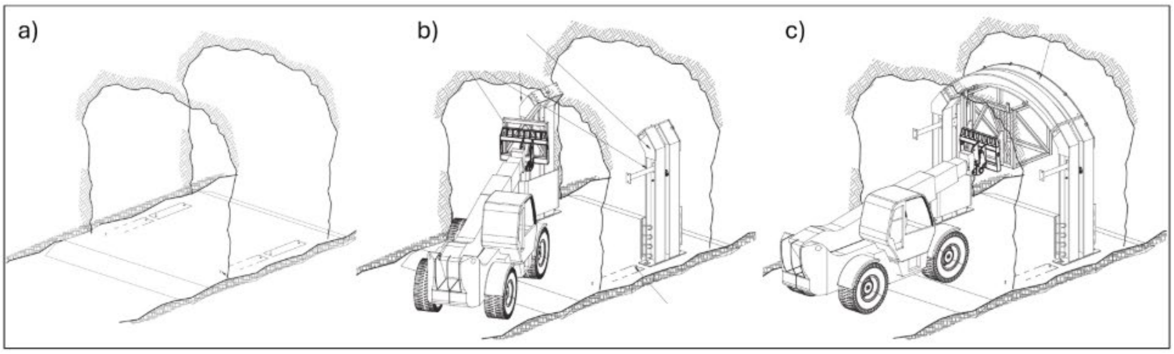


Figure 8 (a) Installation of bolts; (b) Installing side columns; (c) Installing the top arch (Wilshaw Engineering 2021b)

4 Underground observations on performance and preventive measures

4.1 Brow set damage rating system and field assessment for Panel 0 brow sets

Ore extraction in the P0 block of HNL1 drawpoints commenced in 2022. A total of 229 drawpoints were constructed between 2022 and 2024 in the P0 extraction level. To consistently assess the field performance of the installed brow sets, a five-level rating system of brow set damage (R0–R4) was developed. This system classifies brow set conditions based on structural damage, deformation, weld response and brow stability: The levels are:

- R0 – no damage, deterioration or weld distress observed
- R1 – minor damage, with slight bending or the initiation of weld deformation
- R2 – moderate damage, with noticeable bending and early separation at structural connections
- R3 – high damage, with structural tearing, significant weld failures or deformation impairing bogging operations
- R4 – severe damage, with structural collapse or complete brow deformation, resulting in loss of functionality.

Brow set conditions were assessed through this observational framework, incorporating visual inspection, photography and probe hole drilling. A total of 229 drawpoints were assessed using the brow set damage rating system. Overall, 88% of the installed brow sets remain fully functional, with 201 out of 229 drawpoints classified as being in normal to minor damaged condition. The remaining 12% exhibit varying degrees of damage and require ongoing monitoring, specific draw control and localised repair. The classified performance of the P0 brow sets is shown in Figure 9.

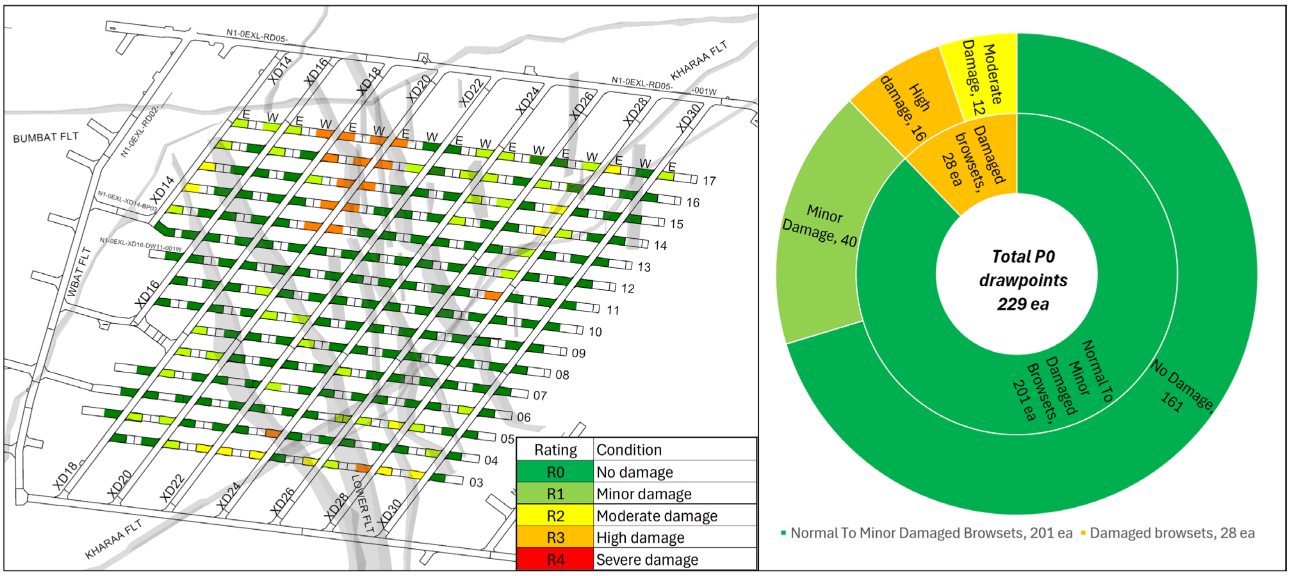


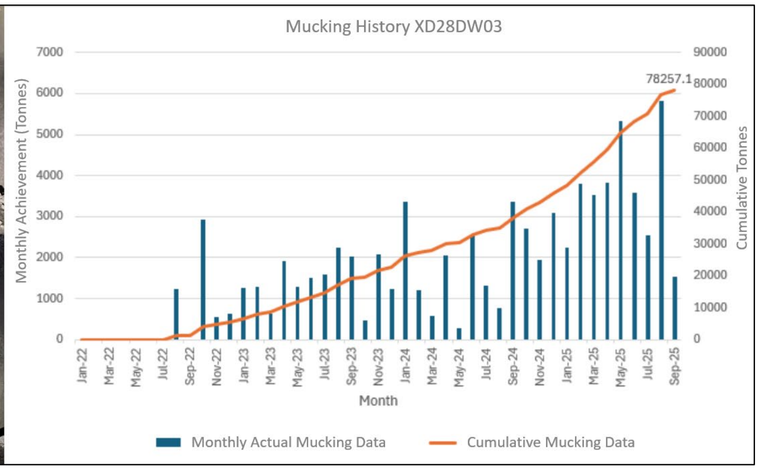
Figure 9 Panel 0 drawpoints' brow set damage condition as of March 2026

The distribution of damaged brow sets is primarily clustered in areas of poor ground conditions and in close proximity to major geological structures. This pattern is consistent with initial geotechnical predictions, which anticipated increased brow wear in zones characterised by weak ground conditions and elevated column heights. Additionally, brow sets located near the caving static boundaries have exhibited comparatively higher levels of damage, likely due to the influence of caving-induced abutment stresses.

4.2 Early brow wear cases and preventive measures

Early brow wear has been observed at several drawpoints in P0, particularly those located within fault zones. One of the earliest examples is the XD28DW03 brow set, situated in the major lower fault zone. An initial indication of brow wear is when the rock brow cable bolt becomes exposed from the drawpoint. This condition indicates that more than 0.5 m of the rock brow has been eroded, as the cable bolt was originally installed at the midpoint of the 1.0 m rock brow. Subsequently, progressive damage to the fourth and third brow sets is observed, indicating that the rock brow has been fully eroded (Figure 10).

(a)



(b)

Figure 10 Progressive damage on the (a) brow set at XD28DW03 and (b) drawn mucking tonnage

When the third and fourth brow sets are damaged, the first and second brow sets typically remain intact. This allows continued draw from the drawpoint while providing sufficient time to implement repair measures, such as the installation of additional brow sets. Early brow erosion has been observed at some drawpoints as early as September 2023, with only approximately 20 kt of drawn tonnage. Although these drawpoints remain operational, this condition highlights the risk of potential early drawpoint closure due to accelerated brow wear. To mitigate this risk, preventive measures have been introduced for P2N caving.

4.2.1 Preventive method for brow wearing

The P2N block caving footprint is larger than that of P0 and intersects the same major fault zones. Based on this geological context and lessons learned from P0 operations, preventive ground-consolidation measures have been introduced for the brow areas within major fault zones in P2N. These include the installation of self-drilling anchor bolts combined with dedicated resin-injection holes(Figure 11).

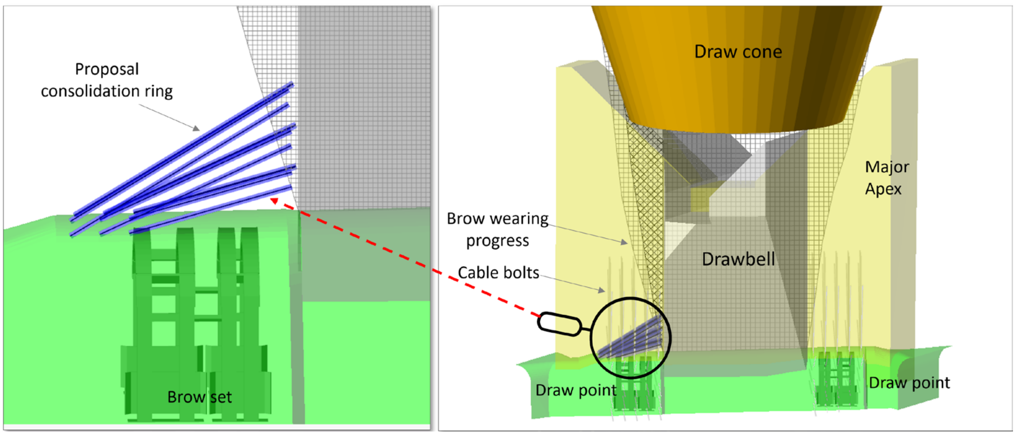


Figure 11 Proposed location of resin-injection holes for the drawpoint brow

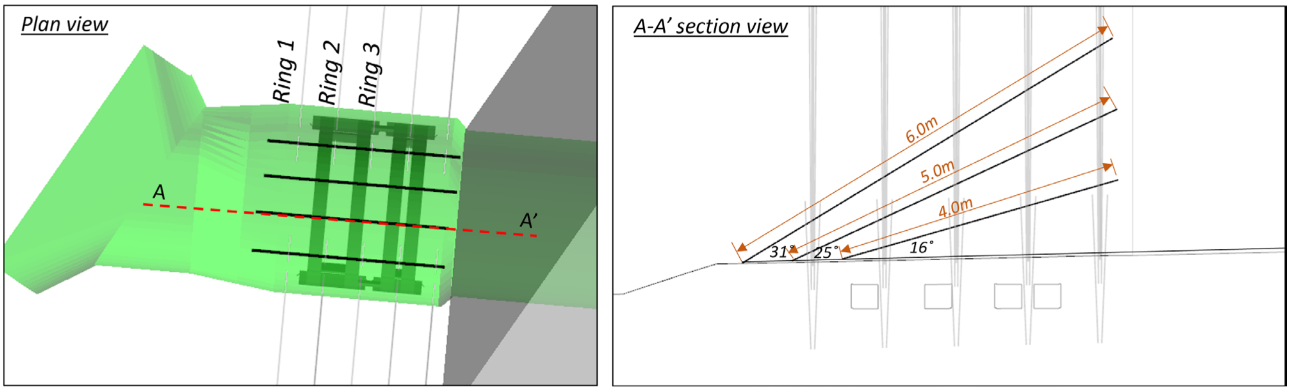


Figure 12 Brow consolidation hole design plan view and section view

Fracture, joint and fault foliation orientations are critical factors in ground-consolidation methods. For example, drilling and resin injection parallel to joint or fault foliation can be less effective as it limits penetration and bonding across discontinuities.

Therefore, the use of self-drilling anchor bolts installed approximately vertical to the brow, combined with resin injection and sub-horizontal dedicated injection holes, ensures more effective and systematic consolidation of the brow zone. Additionally, maintaining an offset of approximately 50 mm between the SDA bolt and the injection hole provides sufficient coverage for dense resin distribution, enhancing confinement and achieving more uniform consolidation throughout the rock mass.

This process improves rock mass confinement by reducing fracture apertures, increasing cohesion and enhancing load transfer across discontinuities into more competent surrounding rock. It expects to mitigate localised ravelling, limits progressive spalling and reduces abrasion-related wear during draw (Figure 13).

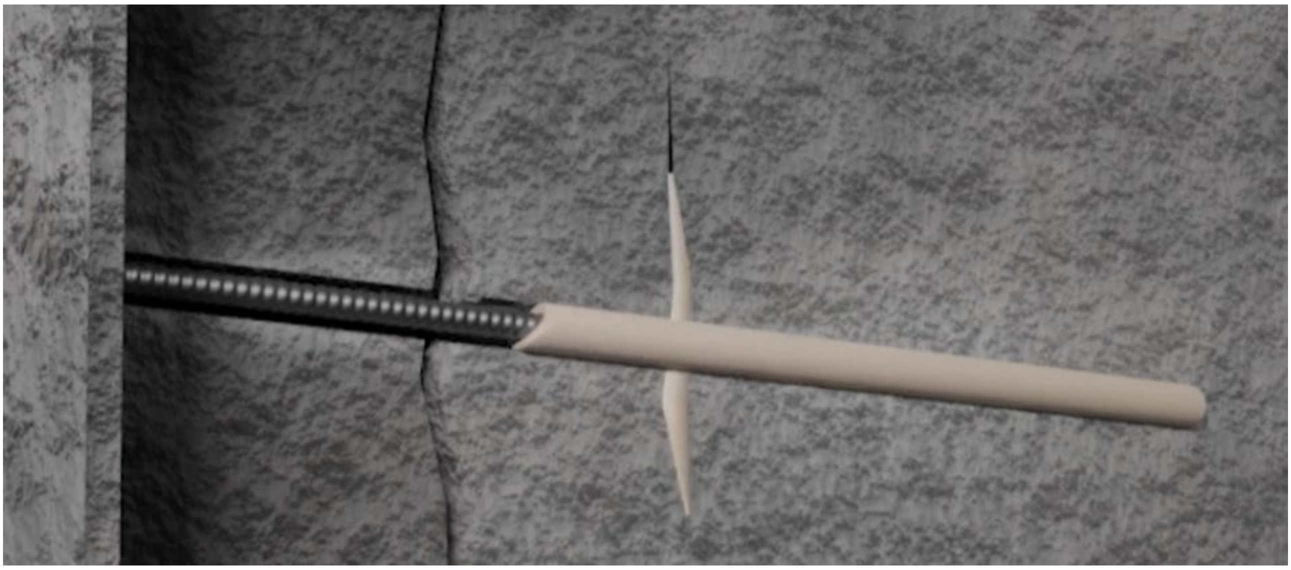


Figure 13 Self-drilling anchor bolts' consolidation mechanism

The expected outcomes are slower brow wear progression, improved brow stability and enhanced operational life of the drawpoints at major fault zones with very poor ground conditions. Further studies will be conducted during P2N production to assess and quantify the effectiveness of these preventive measures.

5 Conclusion

The brow set design for the Oyu Tolgoi mine was developed based on the anticipated production life of the drawpoints and the expected ground conditions. The Hugo North orebody contains several major geological structures associated with very poor ground conditions, and the planned production life of individual drawpoints is relatively long, ranging from 5 to 10 years. Due to the nature of porphyry deposits, zones affected by major structures tend to host higher-grade mineralisation. Consequently, drawpoints located in poor ground conditions represent high-value production areas. Considering these factors, heavy-duty, stiff arched brow sets were selected for implementation in the Panel 0 (P0) drawpoint development. The primary advantage of this design is that the arched top member enables high vertical column loads to be redistributed towards the vertical legs of the brow set, which are the highest-capacity structural elements under vertical loading conditions. These loads are subsequently transferred into the surrounding rock mass, enhancing overall structural performance in poor ground conditions.

Following the selection of the arched brow set design, an installation trial was conducted at the surface facility. This trial identified the long top arch, measuring approximately 4,755 mm, as the most challenging part during installation. As a result, further design modifications were implemented to reduce underground installation time and to improve reinforcement of the concrete infill.

The current performance of the brow sets in P0 indicates that both the original design selection and subsequent design modifications were appropriate. Of the 229 brow sets installed, 201 are classified as normal to minor damaged conditions, and only 28 brow sets are classified as moderately to highly damaged. This indicates that approximately 12% of brow sets have experienced moderate to high damage, while 88% of brow sets continue to perform satisfactorily under high column loading and poor ground conditions. However, early brow erosion has been observed in some highly damaged brow sets, such as XD28DW03, where noticeable brow wear occurred after only 20 kt of production mucking. In response to this observation, preventive measures have been introduced for Panel 2 North (P2N), including pre-consolidation of rock brows located within major lower fault zones. Further studies will be conducted during P2N production to assess and quantify the effectiveness of these preventive measures.

Acknowledgement

The authors would like to acknowledge the contributions of all engineers involved in the design, improvement and installation of the brow sets. The brow set design and its performance are critical to the productivity and operational success of the Oyu Tolgoi underground mine.

Disclaimer

Please note that this paper contains estimates and forward-looking statements within the meaning of applicable securities laws. These statements are based on operational observations, engineering assessments, modelling assumptions and information available at the time of writing, including matters relating to brow set performance, ground conditions, brow wear behaviour, drawpoint service life, preventive measures, operational performance and future improvement programs. Actual outcomes may differ due to geological, geotechnical and operational parameters, construction and other factors.

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