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Maintaining ground support capacity to anticipate stress change episodes in Panel 0, Oyu Tolgoi mine

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Abstract

It is widely recognised that footprint reliability is one of the main indicators to have a safe and productive cave operation, especially during the cave establishment where the footprint will experience stress change episodes. During the cave establishment stage, the undercutting and drawbell construction rate is linked directly to the cave health, where maintaining its rate at the designed level will be relied on to maintain footprint stability. This paper aims to share the selected approach called the preventive support maintenance (PSM) program and its implementation result at Panel 0 (P0), the first operated block cave at Oyu Tolgoi (OT). This approach aims to maintain the rock mass pillar integrity by proactively adding new ground support elements in advance to enhance rather than exhaust the capacity of the original ground support system, which may lead to pillar instability. The robust geotechnical monitoring system established at the mine has contributed to the success of the PSM program implementation and the successful completion of Panel 0 undercutting as per plan. This approach has effectively mitigated the risks of rock mass integrity and associated personnel safety and thereby minimised disruptions to the production schedule.

Keywords: *undercutting, preventive support maintenance, stress changes, displacement monitoring*

1 Introduction

The Oyu Tolgoi (OT) is a world-class porphyry copper and gold mine in the south Gobi Desert in the province of Umnugobi, Mongolia, and distanced 550 km from the capital city of Ulaanbaatar. OT mine consists of a series of orebodies named Southern Oyu, Heruga, Hugo South, and Hugo North. Hugo Dummett, also called Hugo, is the largest of the orebodies and is divided into Hugo North and Hugo South. Hugo North is the first underground orebody to be mined at OT and measures approximately 280 m in width, 2,000 m in length and 600 m in ore column height. It is broken into Lift 1 with the mining panels of P0, P1, P2N, P2S and Lift 2. The OT Hugo North Lift 1 P0 block (OT P0 block), approximately 320 m in width and 280 m in length, developed a production level at a depth of 1,300 m from the surface, employing an advanced undercut method with an apex level. P0 undercutting commenced in January 2022 and was completed by April 2024. Undercutting started in the southwest corner of the footprint and was directed along the major principal stresses. The El Teniente layout, with dimensions of 31 by 18 m, is implemented with a pillar thickness of 17 m between extraction and undercut levels.

The OT P0 block caving is expected to present challenging geotechnical risks in caveability and cave propagation based on high-stress conditions, a highly fractured rock mass (average mining rock mass rating of 40–65), and a sufficient caving footprint. The dominant rock types within the P0 footprint area include quartz monzodiorite (QMD), biotite granodiorite (BiGd), augite basalt (VA), and ignimbrite (IGN), as depicted in Figure 1 with the major geological faults, including WestBat and Lower faults, as well as undercut advances.

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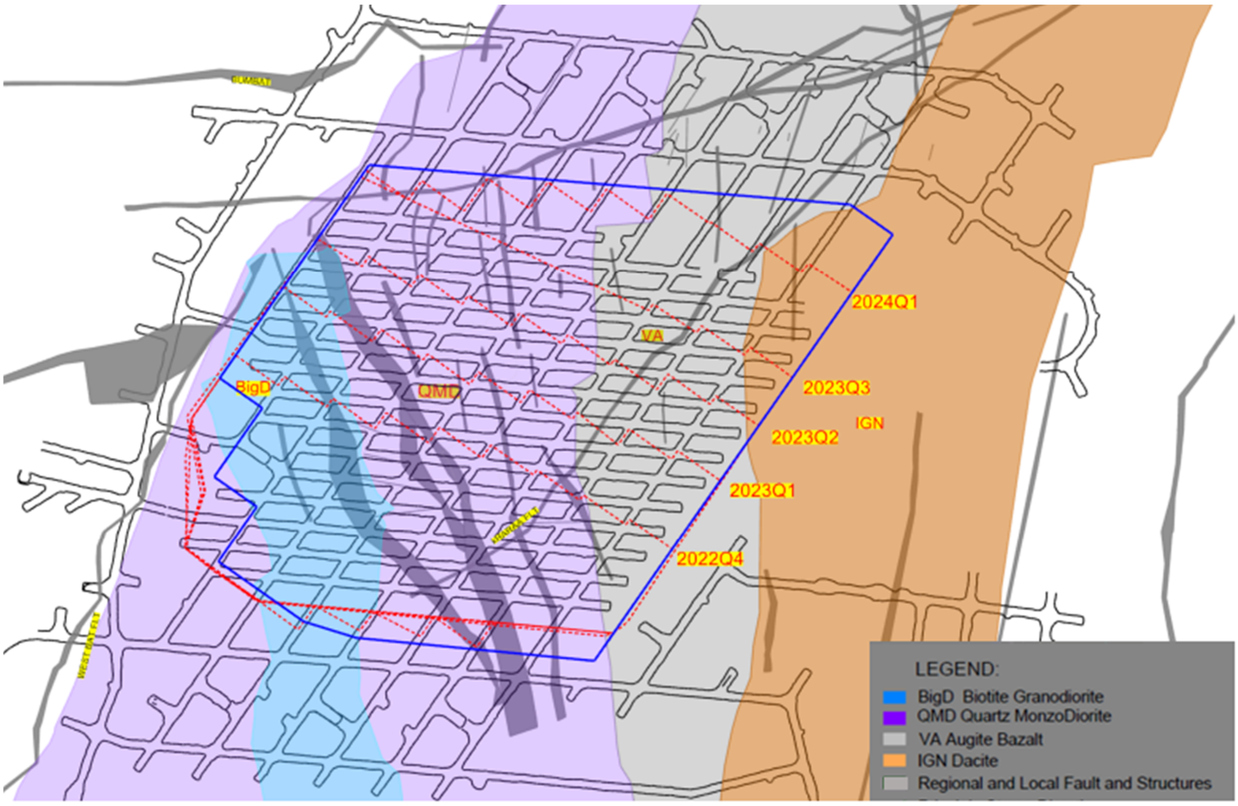


Figure 1 Oyu Tolgoi P0 footprint and undercut advance

The anticipated challenges arising from these conditions emphasise the importance of ensuring excavation stability during both the development and production stages. Intact rock properties of dominant lithologies in P0 footprint are given in Table 1.

Table 1 Intact rock properties of dominant lithologies for Panel 0

Lithology	Alteration	Intact rock properties			
		σ_{ci} (MPa)	m_i	σ_t (MPa)	E_i (Gpa)
BiGd	Unaltered (low vein density)	115.4	17.1	5.50	37.5
	Unaltered (high vein density)	80.4	17.4	3.80	33.3
QMD	Advanced argillic (AAA)	55.7	16	2.80	63.1
	Intermediate argillic (IAA)	78.4	19.4	3.50	57.8
	Phyllic (PHY) (low vein density)	96.5	20	4.20	59.2
	Phyllic (high vein density)	108.8	15.8	5.50	59.2
	Potassic (PTS), propylitic (PRO)	94.1	23.6	3.60	53.8
VA	Advanced argillic	72.2	20.4	3.1	59.7
	Intermediate argillic	72.2	20.4	3.1	56.7
IGN	Advanced argillic	77.5	10	5.10	62.2

This paper aims to investigate the feasibility of implementing the preventive support maintenance (PSM) approach at OT P0, a deep block caving, specifically during the undercutting stage. It seeks to understand how the robust monitoring system utilised at OT P0 enables the estimation and control of rock mass displacement under stress changes. Continuous monitoring and field observations will be employed to assess how PSM restores ground support capacity without causing mining delays during the cave establishment stage in this case study.

1.1 Stress change episodes in caving

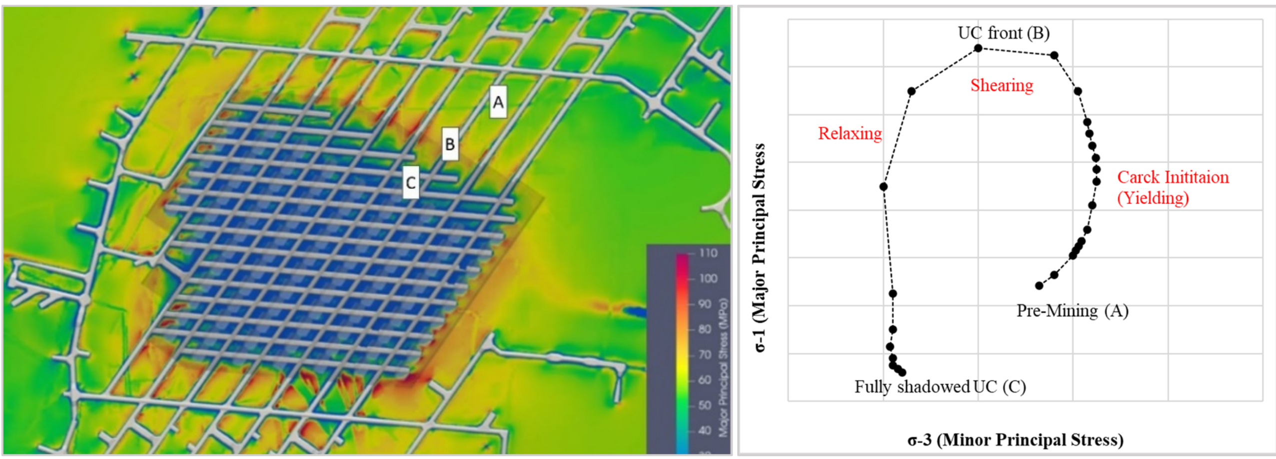
Over-coring of hollow inclusion (Hi-Cell) was completed during the OT underground early development stage; however, results and the assumption are still useful to validate the rock mass response and induced stress changes resulting from the undercutting and the caving. Based on this, an estimate of the stress field at 1,300 m below the surface is presented in Table 2.

Table 2 In situ stresses at 1,300 m below the surface

Principal stress	Magnitude (MPa)	Dip (°)	Bearing (°)
σ_1	57.8	00	055
σ_2	34.5	00	145
σ_3	27.2	90	058

Laubscher et al. (2017) stated that stresses will begin to increase in the undercut (UC) front when undercutting has started. Stress measurements during the undercut stage indicate that increased abutment stresses drop sharply below the undercut area (Rojas 2000). Numerical modelling proves valuable for understanding stress patterns during undercutting. OT developed a cave-scale model to analyse stress changes along with footprint stability. Vertical stress magnitudes ranging from approximately 40–45 MPa are anticipated 50–100 m ahead of the advancing cave front at both undercut level (UCL) and extraction level (EXL). Modelling indicates that the extraction level will experience an average vertical stress of 2.5–5 MPa beneath the actively drawn cave.

Sigma 1 is directed horizontally into the northern undercut face, ranging from approximately 90–110 MPa. However, it then decreases to in situ levels two or three pillars ahead of the undercut front. Ahead of the southern cave face and edges of the cave on the extraction level, Sigma 1 levels are expected to reach 90–100 MPa, while it is lower in the northern face (~70–80 MPa) due to face orientation relative to σ_H. These high induced stresses are able to pass under the cave easily, and so σ_1 values drop to 30–40 MPa within 25–50 m of the cave front on the extraction level. The stress changing episodes is illustrated in Figure 2.



(a) (b)

Figure 2 Abutment stress zones in (a) undercut front; (b) stress pattern adapted (Simanjuntak et al. 2020)

Modelling predicts closure strains for average rock mass conditions up to 5% in the undercut level immediately at the undercut front, decreasing to 2–3% ahead of this and approximately 2% in the extraction drives. These levels are considered indicative of minor to severe squeezing problems (Figure 3).

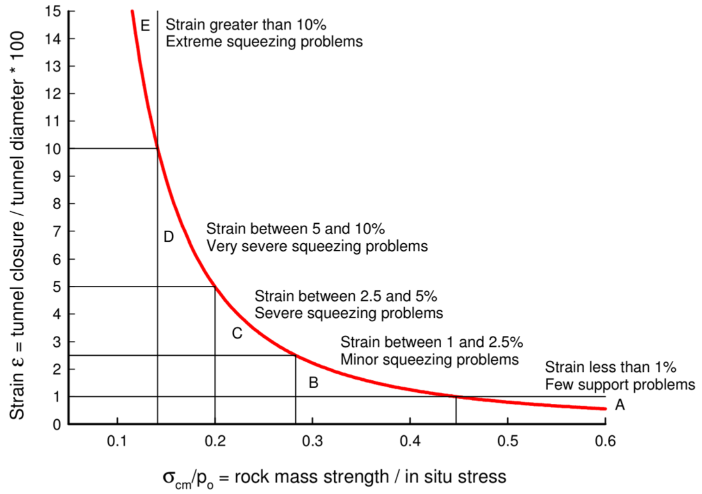


Figure 3 Tunnel damage classifications (Hoek & Marinos 2000)

Due to moderately to highly fractured rock mass conditions, it is anticipated that rock mass failures will predominantly manifest as squeezing and localised brittle failures around excavations, as shown Figure 4.

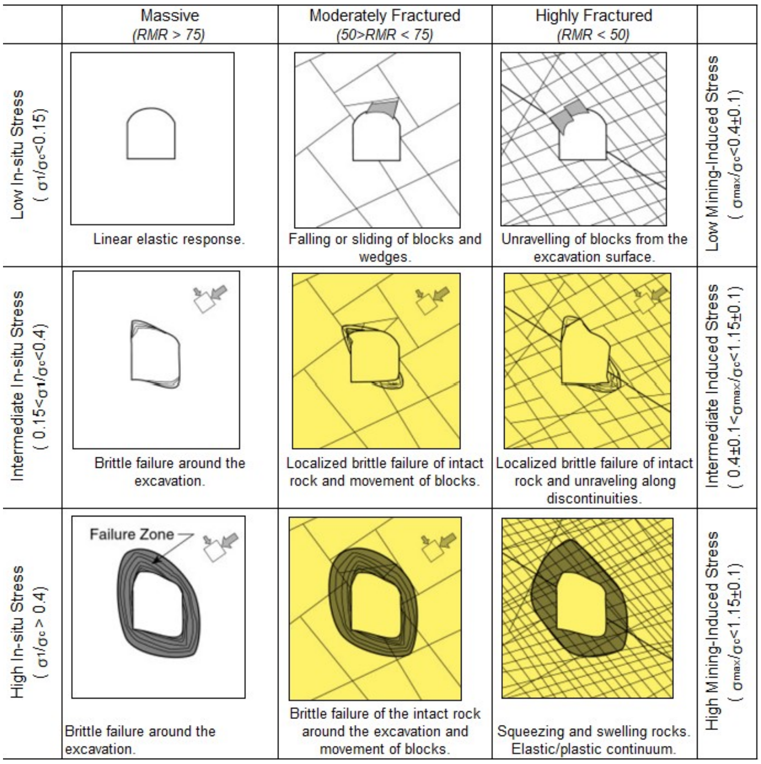


Figure 4 Tunnel instability modes with dominant modes for Oyu Tolgoi P0 highlighted (modified after Kaiser et al. 2000)

1.2 Preventive support maintenance

As mines go deeper, effective ground support becomes a strategic element due to challenging geotechnical conditions for successful mine development and seamless production (Kaiser & Moss 2022). In deep block cave operations like OT P0, maintaining footprint stability, especially in the cave initiation stage, can be one of the operational challenges for safe and undisturbed production or caving.

Bartlett (1992) highlighted that historically, ground support in cave mining is often based on experience. If a failure occurs, the support levels are increased until the support is sufficient. This trial-and-error approach can lead to major operational problems. Kendorski et al. (1983) suggested a phased approach to the installation of support in order to overcome support damage during the retreat of the undercutting stage.

Additionally, Kaiser and Moss (2022) introduced a deformation-based ground support design approach, which means that if support capacity can be consumed, it can also be restored through PSM.

The PSM approach is implemented to OT P0, which is defined as the capability to restore the support system capacity in the early stage using displacement criteria to survive until undercutting is eliminated/passed the concerned/PSM area.

As mentioned in the previous chapter, the initiation of the undercutting and subsequent extractions will induce notable changes in the in situ stress conditions, leading to potential tunnel instability issues. Considering the primary instability modes, implementing a displacement monitoring program and conducting field observations would be effective proactive measures to assess ground deterioration and apply the PSM approach.

1.3 Ground supporting at OT P0

At OT P0, the heaviest ground support ever installed in a block cave mine has been used to prevent pillar failure based on previous caving experiences such as Argyle (Stegman et al. 2018). During the undercutting of the Argyle block caving, high convergence and damage were observed at undercut levels, particularly in areas with poor rock mass. Additional ground support, including de-bonded cable bolts, has been implemented to maintain the stability of these areas. This was achieved by developing a trigger action response plan that incorporates systematic convergence monitoring, damage assessment, ground condition evaluation, and undercut advance (Fernandez et al. 2011).

The primary ground support designs of OT P0 are summarised in Table 3.

Table 3 Ground support types at P0 production levels

Mine level	GS elements	Rim drives		Drill/extraction drives	
		Good ground	Poor ground	Good ground	Poor ground
Undercut and apex	The first layer of FRS*	50 mm		75 mm	50 mm
	Mesh	ST-chain-link		–	ST-chain-link
	Resin bolt	2.4 m (1 × 1 m)		2.4 m (1 × 1 m)	
	The second layer of FRS	75 mm (lower wall only)		–	75 mm (lower wall only)
	Cable bolt	8.0 m (2.0 x 2.0 m)	8.0 m (2.0 × 1.0 m)	–	6.0 m (2.0 × 2.0 m)
Extraction	The first layer of FRS	50 mm		50 mm	
	Mesh	Woven		Woven	
	Resin bolt	2.4 m (1 × 1 m)		2.4 m (1 × 1 m)	
	Second layer FRS	75 mm		75 mm (lower wall only)	
	Cable straps	Internal rim drives only		Side walls and backs	
	Cable bolt (17.8 mm)	8.0 m (2.0 × 2.0 m)	8.0 m (1.5 × 1.5 m)	6.0 m (1.0 × 2.0 m)	8.0 m (1.0 × 1.0 m)

FRS* = fibre-reinforced shotcrete

According to Kaiser and Moss (2022), the support system capacity can be estimated using each support component and the support system displacement capacity. Figure 5 illustrates the support system capacity at OT P0, where the primary reinforcement elements consist of 2.4 m long, 25 mm diameter resin-grouted J-Tech rebars and 17.88 mm full-column cement-grouted cable bolts.

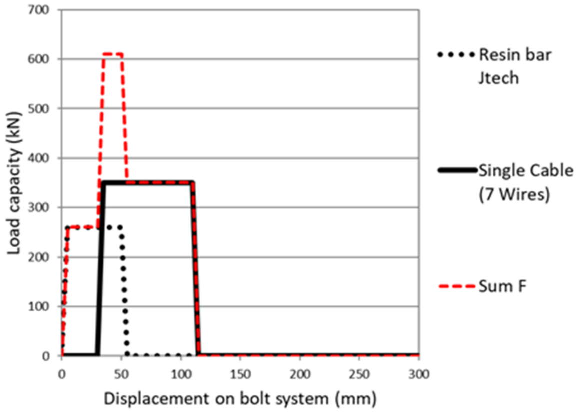


Figure 5 Support system displacement capacity adapted from Kaiser & Moss (2022)

2 Displacement monitoring

The vision of the monitoring at OT operation is not just about the technology, it's also a fundamental component of the commitment to operational excellence and safety. OT production level at Lift-1 1,300 m subsurface requires constant monitoring of the rock mass, because at such a depth the potential rock mass instabilities are the most expected phenomenon; especially for the underground (UG) mass mining operations. A Series of systems and processes to collect complementary/redundant behaviours of the rock mass (for the purpose of monitoring UG infrastructures and the longer-term effects while mining is in progress, because of the high development costs and relative lack of flexibility in terms of the caving method as well as the production level) must remain stable and available for the operation during the planned life of the mine. The monitoring program at OT P0 is primarily categorised into two groups:

1. footprint stability monitoring
2. cave propagation monitoring, which includes observing cave growth, flow, and subsidence monitoring.

During the undercutting stage, the focus of monitoring shifts to the footprint stability. This includes various techniques such as damage mapping (visual inspection), multi-point borehole extensometer (MPBX), convergence measurements using 2-point tape extensometers, lidar (3D) point-cloud scanning, and borehole camera surveys. In this study, particular emphasis will be placed on MPBX and convergence data due to their comprehensive coverage of the footprint area (Figure 6) and continuous measurement capabilities.

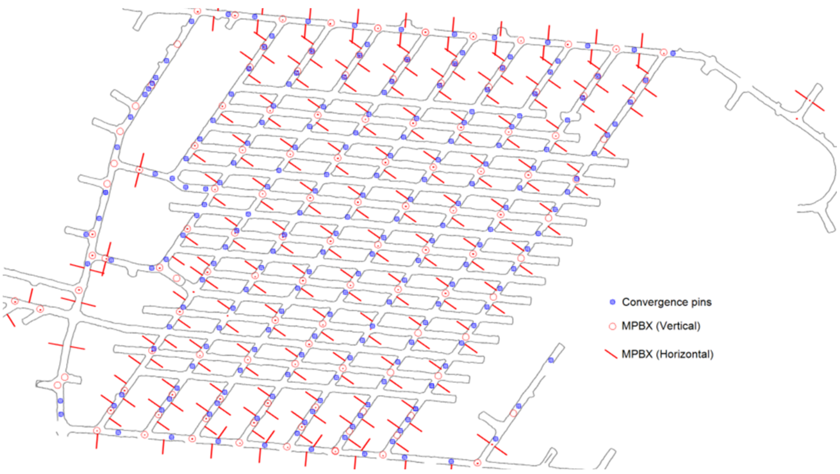


Figure 6 Multi-point borehole extensometer and convergence pins within P0 footprint

These data serve as key references for making quick and precise decisions to anticipate stress changing episodes.

2.1 Multi-point borehole extensometer

The MPBXs that have been customised with six anchors for OT rock mass are an effective tool to predict the ground support consumption and its performance. The typical instrumentation configuration in each monitoring area comprises three MPBXs: one installed vertically in the intersection back and one installed horizontally in each opposing pillar sidewall, as shown in Figure 7.

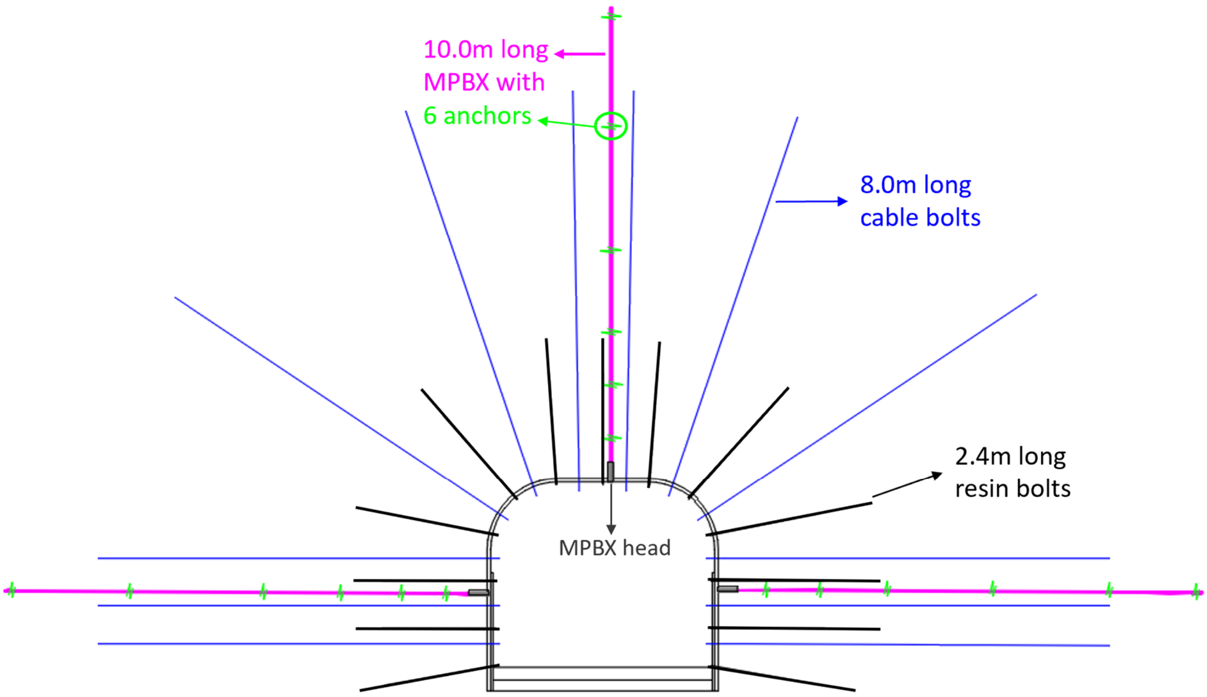


Figure 7 Multi-point borehole extensometer installation position with respect to reinforcement elements

The system is deployed in two phases of installation, before and after UC. Before UC, MPBXs were proposed to predict rock mass deteriorations during undercutting. MPBXs are installed in the alternating pillars across the whole extraction level, and the rim drives around the cave footprint periphery in all three levels, including undercut and apex. Utilising the data obtained by the automatic data acquisition system can be a powerful tool to recognise timely evidence of the instability of the rock mass and allow mitigation activities to stabilise the area.

2.2 Two-points convergence tape extensometer

The tape extensometers measure the distance between the sidewalls of the excavation using convergence pins installed into the FRS of tunnel walls, providing a convenient and simple method for assessing excavation closure. However, this method only captures sidewall or horizontal movements and necessitates manual data collection. A total of 286 convergence stations, spaced at intervals of 10–20 m at both extraction and undercut levels within the perimeter of the P0, are measured weekly.

2.3 Damage mapping (visual observation)

Damage mapping involves field observational inspections to assess the damage levels of ground support elements in the excavation tunnel. Damage mapping is completed on a weekly basis in footprint areas (extraction, undercut, and apex levels) and monthly in off-footprint drives. According to the TARP at OT P0, additional damage mapping is conducted in areas where higher displacement is indicated. Table 4 illustrates the scoring criteria of damage mapping with TARP level, which will be discussed in Section 3.

Table 4 Damage mapping criteria

Damage class	Damage level	Description	TARP level
R0	No damage	No indication of any damage in ground support elements	Normal
R1	Slight damage	Single cracks observed in shotcrete, but no sign of loading in rockbolts	Normal
R2	Moderate damage	Multiple shotcrete cracks observed, with spotted loading evident on rockbolts	TARP PSM-1
R3	Severe damage	Open cracks observed in shotcrete, accompanied by high loading or failures in rockbolts	TARP PSM-2
R4+	Closure	Partial to total closure of the tunnel, estimated displacement is more than 200 mm	TARP 3 or Rehab

Damage mapping was the most effective methodology for evaluating the overall ground conditions. At OT P0, the damage mapping approach divides the tunnel profile into eight sections (Figure 8), including the backs, shoulders, mid-walls, lower walls, and floor; for detailed inspection.

(a) (b)

Figure 8 Damage map and tunnel sections of damage mapping

2.4 Lidar scanning (mobile and fixed)

There are techniques available to assess the severity of damages or convergence on the excavation surfaces in the extraction drives using portable lidar scanners. At OT P0, two primary types of lidar scanning, namely mobile and fixed, are utilised for geotechnical monitoring purposes. Mobile scanning involves mounting the scanner on a light vehicle, allowing for quick data collection of surface profile changes with lower accuracy in the whole extraction drive on a quarterly basis. Conversely, fixed or static scanning, which offers higher accuracy, is employed selectively in specific areas of concern when necessary. An example of lidar scanning data, where changes (displacement, m) in surfaces scanned at two different times are calculated and highlighted in different colour levels, is shown in Figure 9.

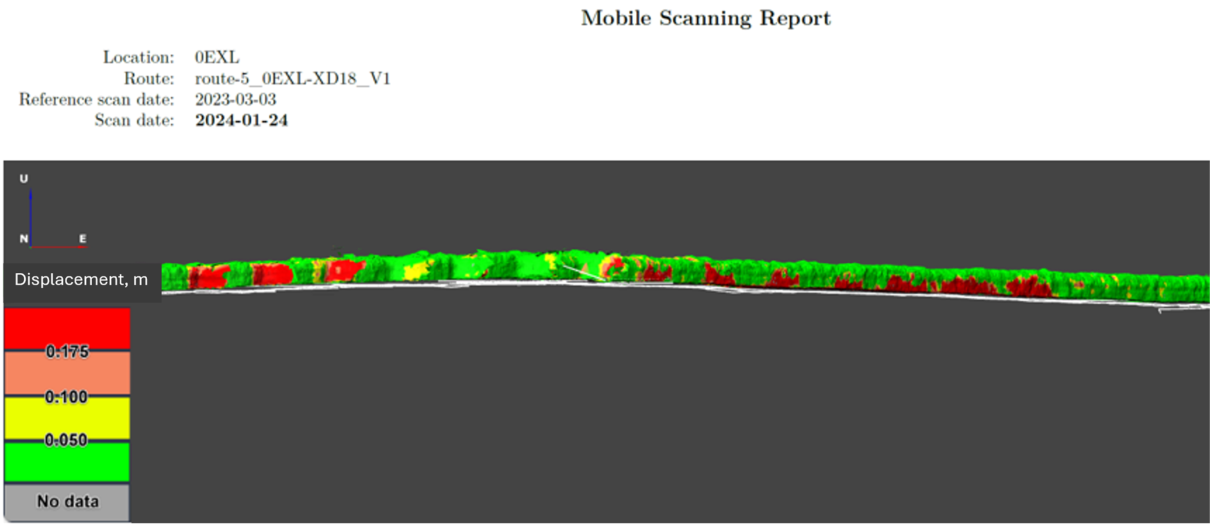


Figure 9 Example reports of Mobile scanning

3 Trigger action response plan for PSM

3.1 PSM area

As illustrated in Figure 10, the footprint area of block caving can be divided into two primary zones based on stress changes during the undercut stage:

1. the abutment stress zone
2. the drawzone.

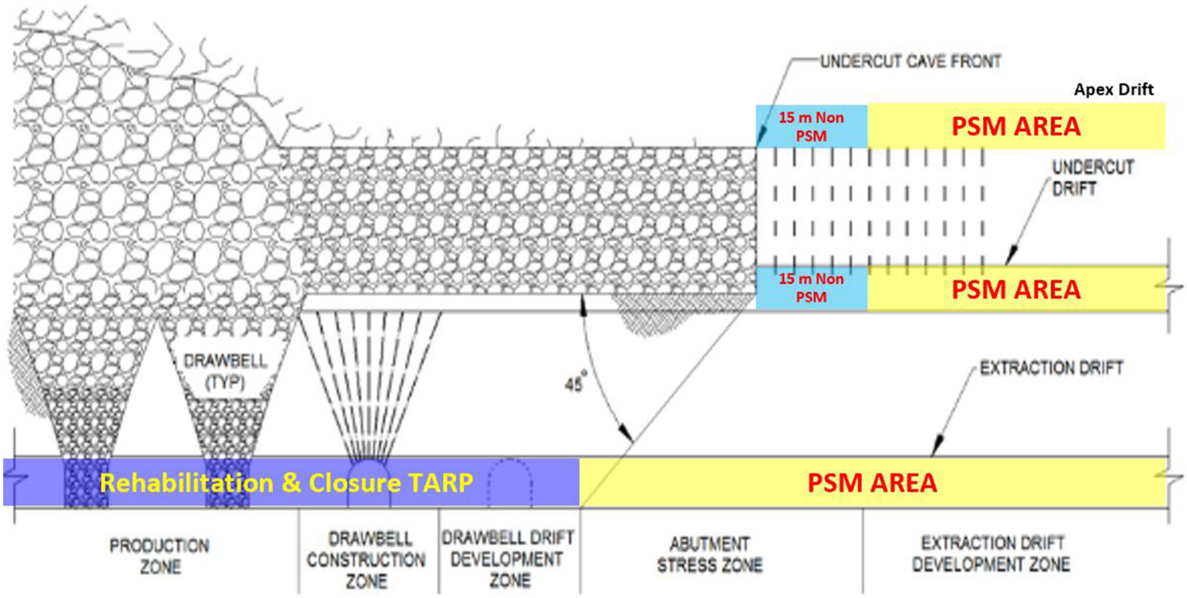


Figure 10 Schematic of PSM area

According to the OT P0 TARP (OT-P0-PSM-TARP 2021), PSM is specifically designed for the abutment area, where potentially highly stressed ground conditions predominate on production levels and ground instability issue on these levels will directly impacting the cave establishment progress leading to production schedule delays. This includes:

- In the extraction level, the abutment area including approximately 20 m behind the undercut face (by the 45° rule of thumb).

- In undercut and apex levels, the area in front of the undercut face, excluding 15 m of the undercut brow.
- All rim drives at each level.

3.2 TARP levels

The TARP levels are determined for restoring the displacement capacity of the reinforcements in ground support by PSM. The first PSM level is activated when the deformation of the tunnel wall reaches 75 mm or 80% of the total installed system capacity, based on the displacement capacity of the installed reinforcements and their installation sequence. Subsequently, the second PSM level is triggered when the displacement reaches 150 mm or 80% of the latest installed element. If the tunnel wall movement exceeds 200 mm, rehabilitation work is required, involving stripping the wall, as it is assumed that the rock mass has completely failed at this level.

A PSM TARP has been developed at OT P0 to respond to each level of cumulative displacement or rate of displacement, as well as ground support damage level, as summarised in Table 5, to maintain ground support capability during the undercut process. When the displacement or ground support damage triggers a PSM level, a PSM work order (WO) will be issued to install additional reinforcement (cable bolts) in the affected area.

Table 5 PSM TARP

Trigger level	Cumulative single wall displacement	Single wall displacement rate (for a week)	Ground support	Response
Normal	<25 mm	<1 mm/day	No damage	No action
	25–7 5 mm	1–2 mm/day	Slight damage	Highlight the area Field inspection Increase the frequency of displacement monitoring
Level 1 PSM	75–150 mm	2–3 mm/day	Moderate damage	Barricade the area Field inspection Issue PSM stage-1 work order Increase the frequency of displacement monitoring
Level 2 PSM	150–200 mm	2–3 mm/day	Moderate damage	Barricade the area Field inspection Issue PSM stage-2 work order Increase the frequency of displacement monitoring
Level 3 Rehab plan	>200 mm	>3 mm/day	Heavy damage	Barricade the area Field inspection Issue rehab plan

3.3 PSM work orders

Before issuing a PSM work order, the geotechnical team conducts a thorough investigation of the affected area's geotechnical and mining conditions. This investigation includes field inspections, damage mapping, and checks on the undercut sequence, blasting, and mucking performance to enhance understanding of displacement behaviours and primary contributing factors. Figure 11 illustrates the PSM flow chart.

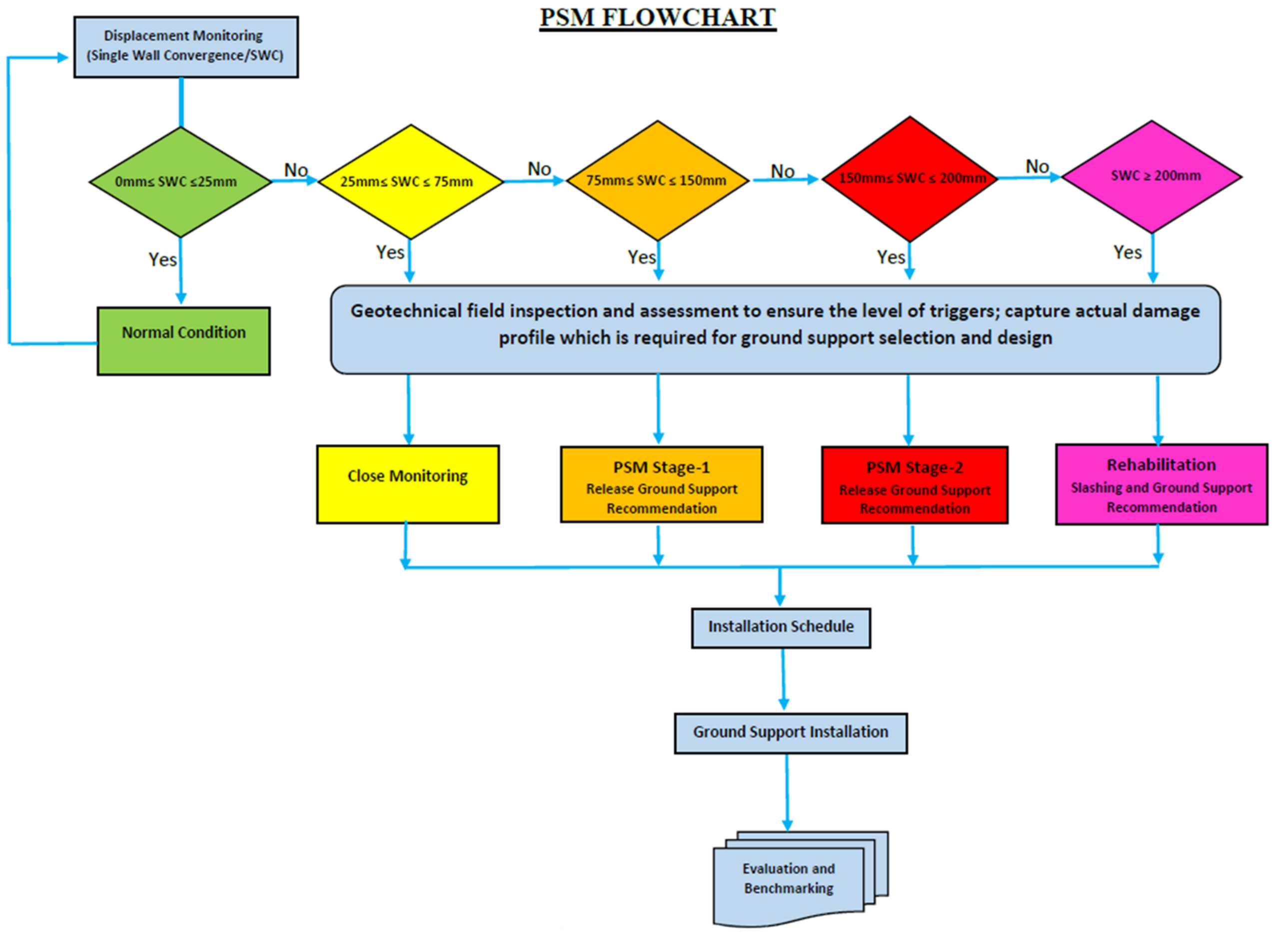
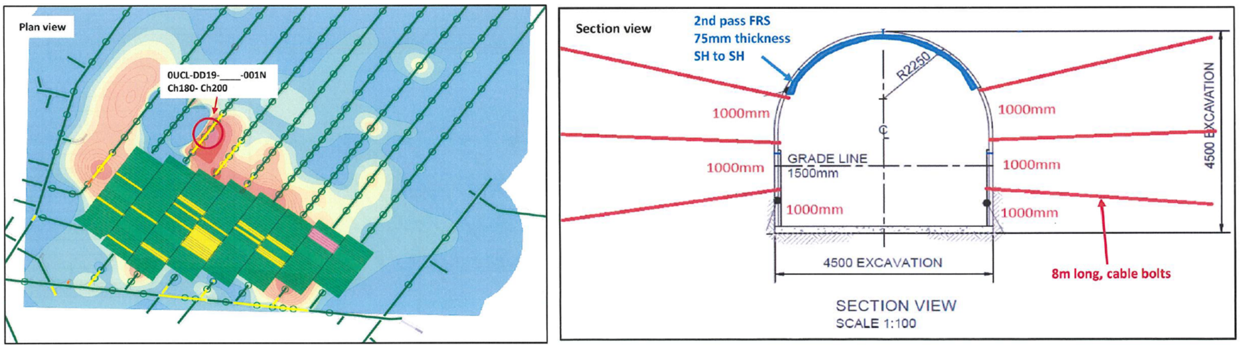


Figure 11 Preventive support maintenance flow chart for OT P0 (OT-P0-PSM-TARP 2021)

Typically, cable bolts with lengths ranging from 8.0–10.0 m and spaced at intervals of 2.0 by 2.0 m are planned for inclusion in the PSM work order, as illustrated in Figure 12.



(a) (b)

Figure 12 Example of preventive support maintenance work order: (a) Area map; (b) Section of additional cable bolting

These cable bolts are strategically placed on the back or sidewall of the excavation, aligning with the direction of deformation. This type of bolting with increased spacing aims to minimise potential delays associated with additional support installation within the advanced undercutting process's tight schedule.

3.4 PSM database

An integrated dataset has been developed to assess the effectiveness of PSM application at OT P0. This database includes key parameters, such as geological and geotechnical conditions, displacement monitoring data, undercut sequences, and PSM work orders for each PSM area.

- **Geological and geotechnical condition assessment:** This involves gathering information on the rock type or geotechnical unit, the vicinity of major geological structures, primary ground supports, and overbreak (OB) values to characterise the PSM area.
- **Undercutting status:** This section involves confirming undercut rules, including lead-lag, undercut rate, drill and blasting performance, and swell removal records, to identify any mining factors contributing to convergence.
- **Deformation monitoring:** All collected geotechnical monitoring data, including displacement data from MPBXs and tape extensometers, damage mapping, and scanning results, are analysed to understand the deformation behaviour of the area.
- **Post-monitoring:** Continuous monitoring, possibly with increased frequency, is conducted during and after PSM implementation to assess the feasibility of the PSM approach, as shown in Figure 13.

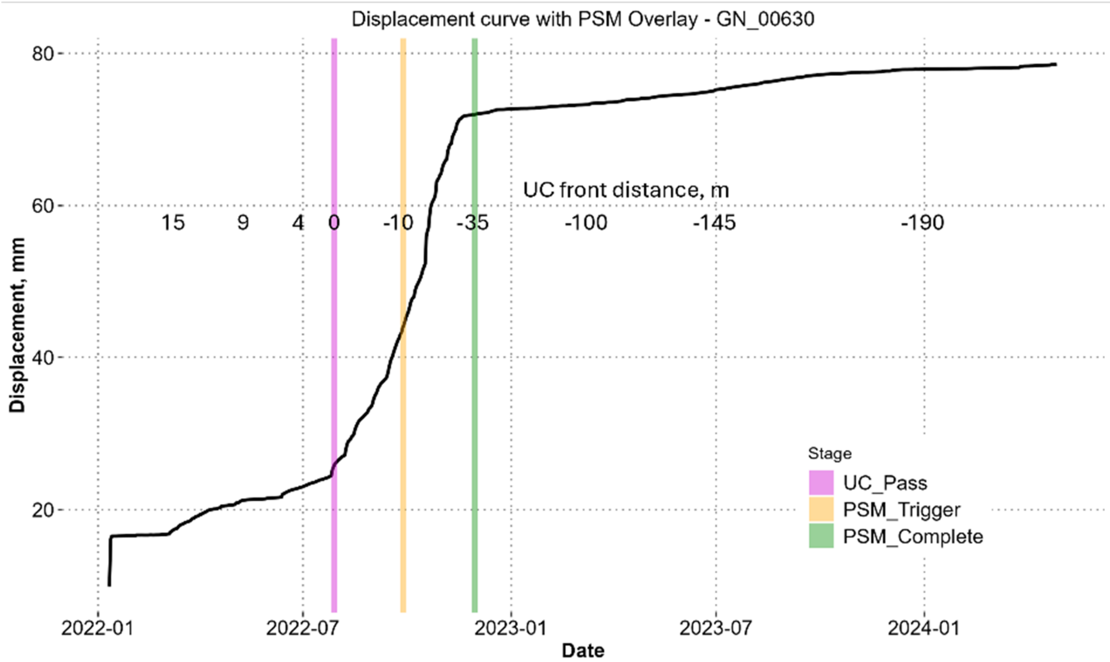


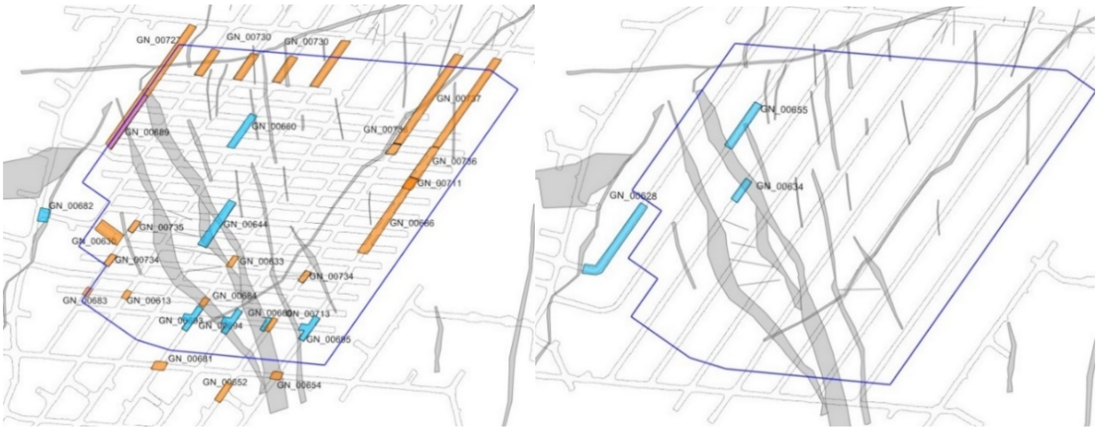
Figure 13 An example of displacement monitoring is overlaying with preventive support maintenance (PSM) work dates and undercut (UC) pass-over

When the combined dataset is created, PSM areas can be classified based on displacement behaviour and potential contribution factors by investigating correlations between key geotechnical parameters and displacement monitoring data.

4 Result

4.1 PSM area characteristics at OT P0

During the undercut stage of Panel 0, over 30 PSM work orders were installed in both extraction and undercut levels. The majority of the PSM areas were situated near the cave outline or static cave boundary, and the areas continued experiencing high-stress conditions and increasing stress levels following the undercut advance. Additionally, these PSM areas were in the vicinity of major geological structures (Figure 14).



(a) (b)

Figure 14 The preventive support maintenance (PSM) areas in (a) extraction level and (b) undercut level. The colour indicates the position of the PSM cable bolts at backs (orange) and sidewalls (cyan), grey polygons indicate major fault zones

The Northern PSM areas, which were influenced by high abutment stress from the undercut front, were directly related to an undercut rate. Overall, the undercut rate was very consistent, except in the northern area, where the rate was only 3.4 m per month. This slow rate was attributed to non-mining-related delays, in contrast to an average rate of 12 m per month across the entire footprint. Four primary types of PSM areas can be classified based on the position of these areas relative to the undercut areas, which are respected with each PSM date (Table 6).

Table 6 Preventive support maintenance area types are respected for the position of the undercut (UC) outline

PSM area type	Affected area (m)	Percentage	Description
Undercut front	216	23%	Triggered at the front (around 40 m at undercut level and 25 m at extraction level) of UC advance
Undercut shadow	186	20%	Triggered just after UC passed over (5–10 m)
Cave boundary (front)	66	7%	Not related to UC advance but close to (<45 m) cave boundary
Cave boundary (shadow)	456	49%	

Another common characteristic of the PSM areas exhibited a significantly higher overbreak percentage during the mining of the excavations compared to the average overbreak across the entire P0 development, as depicted in Figure 15.

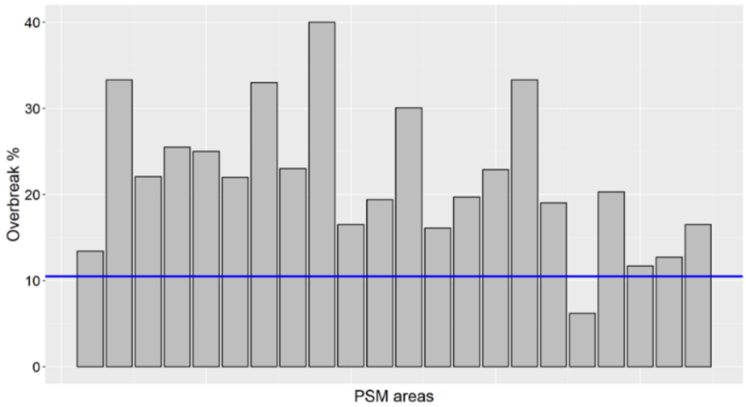


Figure 15 Development overbreak (OB) for preventive support maintenance areas: the blue line shows the average OB for the P0 footprint

The primary reason for the higher overbreak observed during P0 footprint development was poor ground conditions or influences from geological structures. Thus, it is evident that poor ground conditions are one of the primary factors contributing to high displacement during the undercutting.

4.2 PSM reliability by displacement monitoring

The integrated monitoring system at OT P0 serves not only as a proactive tool for detecting rapid or significant rock mass displacement and tunnel wall deformations, but also aids in understanding the effectiveness of the PSM approach in mitigating high abutment stress damage. It is worth noting that this study aims to quantitatively explore the feasibility of PSM application. Therefore, displacement rates both before and after PSM installations are compared using real-time MPBX or frequent tape extensometer measurements. Displacement rates were calculated within a 2-week window for both before and after monitoring to observe the immediate response to PSM installations, aligning with the frequency of convergence measurements (Figure 16).

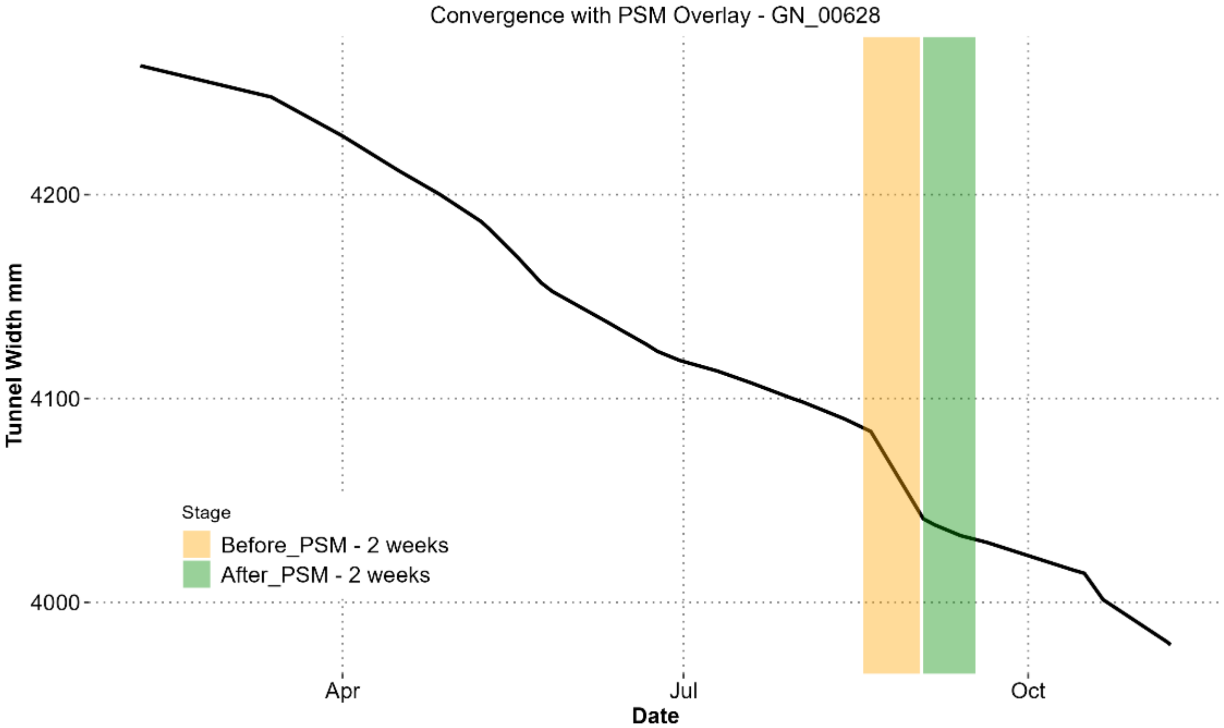


Figure 16 Example of convergence measurements overlain with preventive support maintenance work order timeline

Table 7 summarises the displacement variances for PSM areas with continuous displacement monitoring data.

Table 7 Displacement monitoring performance before and after preventive support maintenance installation

PSM area		Displacement rate (mm/day)		PSM effectiveness
Type	Number	Before PSM	After PSM	
Undercut front	2	1.34	1.22	Slightly maintained
Undercut shadow	1	1.04	0.17	Maintained
Cave boundary (front)	3	0.32	0.24	Slightly maintained
Cave boundary (shadow)	9	0.31	0.15	Maintained

4.3 Ground damages at undercut stage

Ground support damages in the P0 footprint were managed to minimal levels during undercutting. This was based on damage mapping of over 4,000 m of excavations at the extraction level after undercutting was completed, as shown Figure 17.

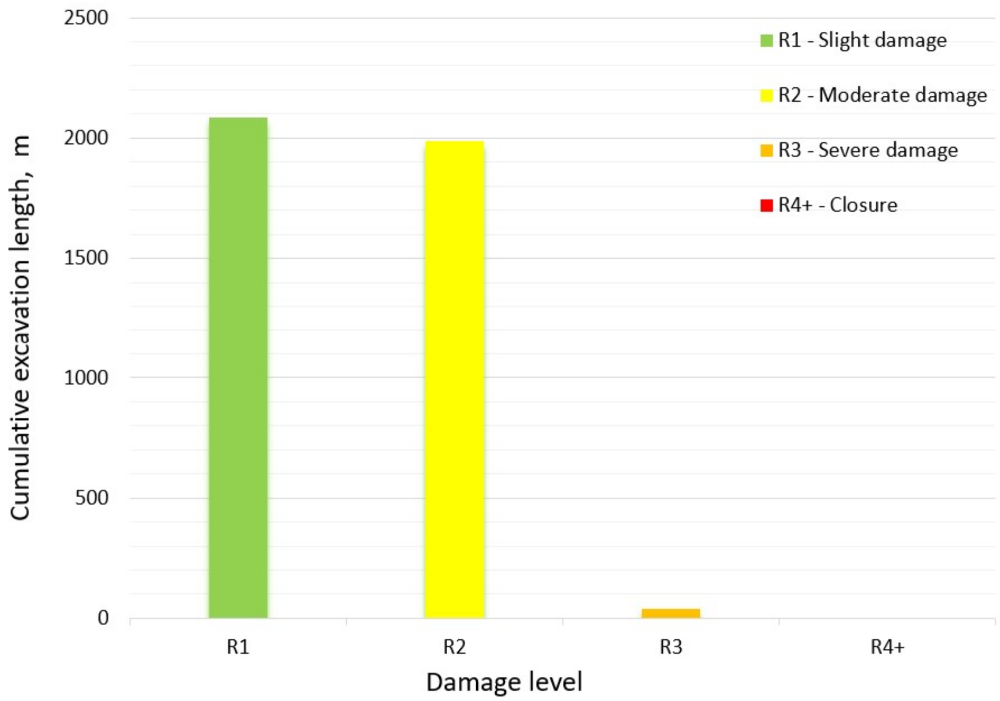


Figure 17 Damage levels of the extraction level excavations after undercutting

Specifically, only 1% (40 m) of total extraction drives were severely damaged or classified as TARP Level-2, 48% (around 2,000 m) were moderately damaged or TARP Level-1 and more than 50% (over 2,000 m) of drives were slightly damaged or in normal conditions.

5 Conclusion

As anticipated, high deformation areas have been affected by the conjunction of major faults and high abutment zones (undercut front and cave boundary). Within these moderate to highly fractured rock masses, displacement monitoring has been an effective and proactive approach to assessing rock mass damage. However, it is important that displacement monitoring measures are validated with field inspections and aerial survey, including damage mapping and LiDAR scanning, to enhance the expedience of PSM TARP.

Analysis of the available continuous displacement monitoring data during PSM work reveals that displacement rates in all types of PSM areas stabilised to some extent. It is worth noting that the continuity and integrated database of geotechnical monitoring were key to assessing the effectiveness of PSM.

Overall, there have been no incidents of ground falls from a safety perspective, nor any delays to undercutting due to ground support rehabilitation. These outcomes suggest that the PSM approach, along with enhanced geotechnical monitoring, reinforced ground support, appropriate mine design and sequencing, and strict cave management and undercut rules, have been effective strategies implemented at OT P0.

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