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A geotechnical review of the transition from narrow incline undercut to w-undercut design at the Deep Mill Level Zone mine, PT Freeport Indonesia

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Abstract

The Deep Mill Level Zone (DMLZ) panel cave mine is located at PT Freeport Indonesia's operations in Papua, Indonesia. Originally designed and constructed with a narrow incline undercut design with 15 m pillar spacing between parallel drill drives, the DMLZ mine experienced significant issues related to seismicity, damages and rockbursts in undercut and extraction levels during undercutting and production. One of the mitigations identified was to transition the undercut design to a wide-undercut (w-undercut). A w-undercut design doubles the spacing between drill drives to 30 m, which reduces extraction ratios and increases the size of the major apex. A transition from the narrow incline undercut design to a w-undercut layout was initiated through slot blasting towards the existing cave. A critical challenge associated with the transition included the initiating slots which were located near high-stress and rockburst-prone ground. Following the interconnection, a systematic investigation of the ground response in the first four drill drifts of the w-undercut layout was undertaken. A substantial improvement in the rock mass behaviour has since been observed in the undercut level, including reduced rockburst frequency and severity as well as an overall decrease in excavation deformation and ground support rehabilitation requirements. This paper discusses the geotechnical review of the narrow incline undercut and w-undercut layout in terms of the ground response due to stress along the cave abutment, seismicity and rockbursts, as well preventative support maintenance.

Keywords: *w-undercut, displacement, transition, rockburst, major apex*

1 Introduction

The Deep Mill Level Zone (DMLZ) is the third lift of the panel caves block within the East Ertsberg Skarn System (EESS) deposits and one of the active cave mines in the Grasberg mining complex. The production level was established 1,600 m below the surface in a massive rock mass and a high-stress environment. Figure 1 shows all the past and currently operating mines in the Grasberg mining district.

The undercut layout and sequence are critical factors in managing ground response to associated seismicity and rockburst damage. A narrow incline undercut layout with the advance undercutting technique has been used in the DMLZ-PB1 and in some areas in the PB2. Cave-induced stresses were realised in the abutments, resulting in extensive damage and rockburst at the extraction and undercut level in DMLZ-PB1 and some in PB2 that required repair work, thereby slowing the production ramp-up.

The evaluation and adoption of a w-undercut layout was identified as an effective way of reducing the potential risk of damage as this layout improves the geometry of the major pillars, thereby reducing the stress level and providing more effective stress management. The undercut design transformation from a narrow

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inclined undercut layout to a w-undercut is also part of the ground control plan to improve the robustness of the pillar to protect it from higher rockburst threats in DMLZ-PB2.

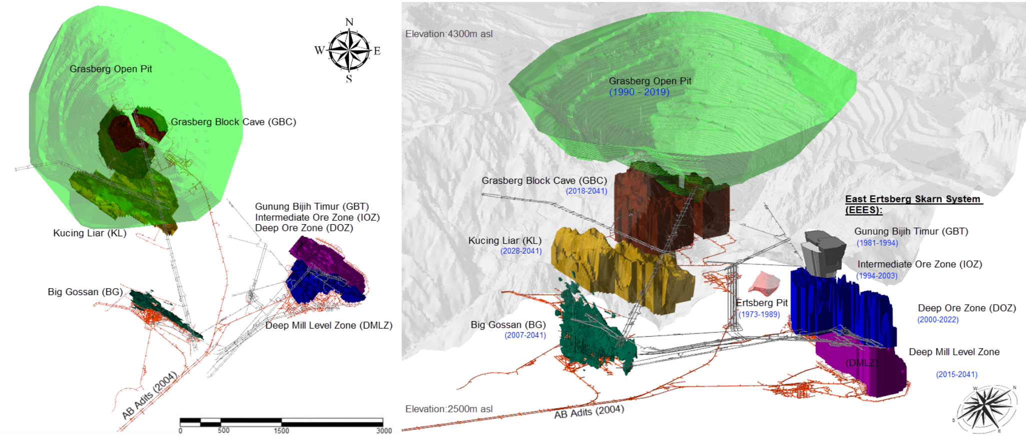


Figure 1 Overview of PT Freeport Indonesia's mining district (Casten et al. 2020)

2 Geology and geotechnical setting

The lithology of the DMLZ-PB2 comprises Ertsberg diorite intrusive and alteration units such as skarn, hornfels and marble. The diorite hosts the porphyry-style mineralisation of the DMLZ deposit, characterised by stockwork and/or sheeted veins of anhydrite quartz. Meanwhile, within the exoskarns near the marble contact in the hanging wall of the orebody, a zone of leached and oxidised skarn exists. This zone generally comprises weaker and more heavily fractured skarn with the marbles. A broken zone with RQD < 25% was also identified at the northern side of the DMLZ footprint within the marbles in the hanging wall of the orebody. Figure 2 shows the geological domains at the DMLZ mine and representative core photos. The predominant fault pattern in the sediment-hosted skarn is northwest striking, with less frequent northeast-trending faults. The structural pattern in diorite displays similar frequencies of northeast-trending and northwest-trending faults, with trace occurrence of north–south fault direction (Haflil et al. 2020).

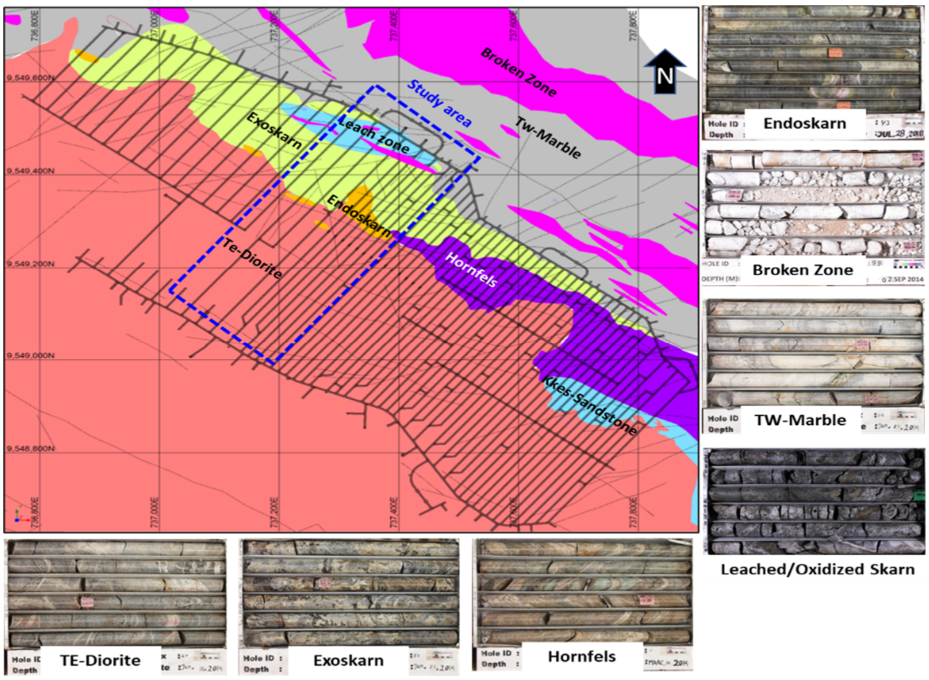


Figure 2 Plan view of lithology domains at DMLZ undercut 2600 L footprint and corresponding core photos for each domain

More recent characterisation work in the DMLZ revealed that rock masses are less jointed than initially estimated. Analyses of fracture frequency data showed a fracture frequency of 0.2/m (one fracture every 5 m) in diorite and 0.3/m (one fracture every 3 m) in skarn, respectively. Due to the limited presence of natural discontinuities (i.e. open joints and fracture frequency), stress-induced fracturing is the typical mechanism influencing the behaviour of the rock mass near the mine excavations. The DMLZ footprint was generally in diorite domain with a mean intact rock strength of 160 MPa. The exoskarn and marble domain in the northern side of DMLZ-PB2 footprint shows less strength compared to diorite, with intact rock strengths of 135 MPa and 95 MPa, respectively. The geotechnical parameters of intact rock in DMLZ-PB2 are presented in Table 1.

Table 1 Representative geotechnical parameters for the DMLZ PB2 (PT Freeport Indonesia 2019)

Geotechnical domain	UCS (MPa)	Ei (GPa)	Poisson's ratio, v	Density (g/cm^3)
Te Diorite	160	53	0.29	2.7
Endoskarn	160	55	0.27	3
Exoskarn	135	68	0.25	3
Hornfels	180	70	0.28	2.9
Tw marble	95	46	0.26	2.8
Broken zone	40	20	0.22	2.7

The prominent risk of mining at depth is the increased in situ stress magnitude, while excavation and cave development create greater induced stress, leading to an environment of increased ground deformation and rockburst. The latest in situ stress measurement conducted by WSP (formerly known as Golder Associates [2018]) indicated that in situ major principal stress is sub-horizontally oriented with the direction trending approximately north-northwest or south-southeast. This observation is in line with the regional earthquake focal mechanisms and tectonics. Stress magnitude can be divided by metre depth (z) as presented in Table 2. The estimation of sigma 1 (σ_1) and sigma 3 (σ_3) in the DMLZ mine is around 58 and 26 MPa, respectively.

Table 2 Representative principal stress magnitude and orientation in DMLZ (Golder Associates 2018)

Criteria	Sigma 1	Sigma 2	Sigma 3
Magnitude	12 +0.027z (mean)	0.022z (mean)	0.015z (mean)
	5+0.027z to 22+0.027z (range)	0.02z to 0.027z (range)	0.01z to 0.02z (range)
Trend	40°	215°	309°
Plunge	22°	68°	02°

3 Undercut layout and blasting achievement

Mining layout and pillar geometry are critical factors in managing global stability and reducing the geotechnical risk profile. The design of the undercut and the sequencing of the undercutting take on the role of providing a facility to reduce the effects of the induced abutment stress. The magnitude of abutment stress is a function of regional stress, the direction of undercutting and the undercutting technique (Laubscher 2000). The important aspect of the undercut technique is to determine the shape of the major apex.

A narrow incline undercut layout with an advance undercutting technique was implemented in the DMLZ-PB1 and in some areas in PB2. This design uses two undercut drill drives (DD) per drawbell (DB), with 15 m spacings between DDs. The sill pillar between undercut and extraction level is approximately 12 to 17 m thick, and the height of the major apex is approximately 33 to 34 m above the floor of the extraction level. Situated in a massive brittle rock mass condition (diorite UCS 160 MPa), the DDs and panels in DMLZ-PB1 and the original PB2 areas were exposed to brittle rock failure mechanisms such as quasi-static spalling and rockbursting. In the early production years, cave-induced abutment loading caused severe rockburst damage that impacted as long interruptions to production and undercut blasting activities due to rehabilitation work.

Based on a recent study from Roy et al. (2023), strainbursting is the main rockburst damage mechanism in the DMLZ-PB1. The majority of the rockburst clusters (67%) clearly coincided with blasting, which occurred adjacent to the cave front (e.g. undercut ring blasting and DB blasting) and initiated a flurry of seismic activity within the abutments. Strainbursting in the narrow incline undercut layout in DMLZ-PB1 has impacted to fully consume ground support system capacities and fails to reinforce the bulked ground. Also, the increasing of abutment loading as the cave advances results in the pillar yielding and requiring ground support to provide extra capacity. Additionally, a flat cave shape induced the advancing cave front abutment stress orientation to become more horizontal, which led to shear failure of the pillar. Various geotechnical strategies were implemented to improve cave shape and growth while redistributing stress levels, such as hydrofracturing and pre-condition blasting, and updating the caving management plan (CMP) and revising the undercut layout in DMLZ-PB2 were undertaken.

The adoption of a w-undercut layout has indicated a significant reduction in induced stress by increasing the dimensions of the pillars between DDs, as presented in the stress redistribution analysis in Figure 16. This method has been successfully implemented in New Afton mine, Canada. The w-undercut layout comprises DDs in the centre of the DB, and a drift is developed over the top of the major apex to provide a check on the accuracy of the drilling while also acting as an anti-socket drift (Apex drift). This technique ensures stresses are well distributed to the wider pillar between DDs. Unlike the narrow inclined undercut layout, the stresses are loaded on the smaller pillar. The first w-undercut blasting was carried out in DMLZ-PB2 DD27 on 17 February 2023.

A comparative review of the new w-undercut layout within a comparative study area was necessary to assess the geotechnical performance of the pillars and the overall layout. The first four w-undercut layouts (DD27–DD30) and four narrow inclined undercut layouts (DD24W-DD27E) were evaluated. Figure 3 outlines the study area, which compares two undercut layouts including drift profile and drill drive arrangement.

The undercutting sequence in DMLZ-PB2 adopted a V-shaped model to double up the cave front (north and south) and to increase the undercutting rate (Nugraha et al. 2022). The slots blasting is positioned near the boundary contact between skarn and diorite, as shown in Figure 4. Orienting the undercut face parallel to the strike of a fault is not favourable due to the possible development of large excess shear stress zones along the fault, which maximises the area's potential for seismic events. The chevron design for DMLZ-PB2 better orientates the cave front against northeast-trending structures by puncturing through the faults at an oblique angle.

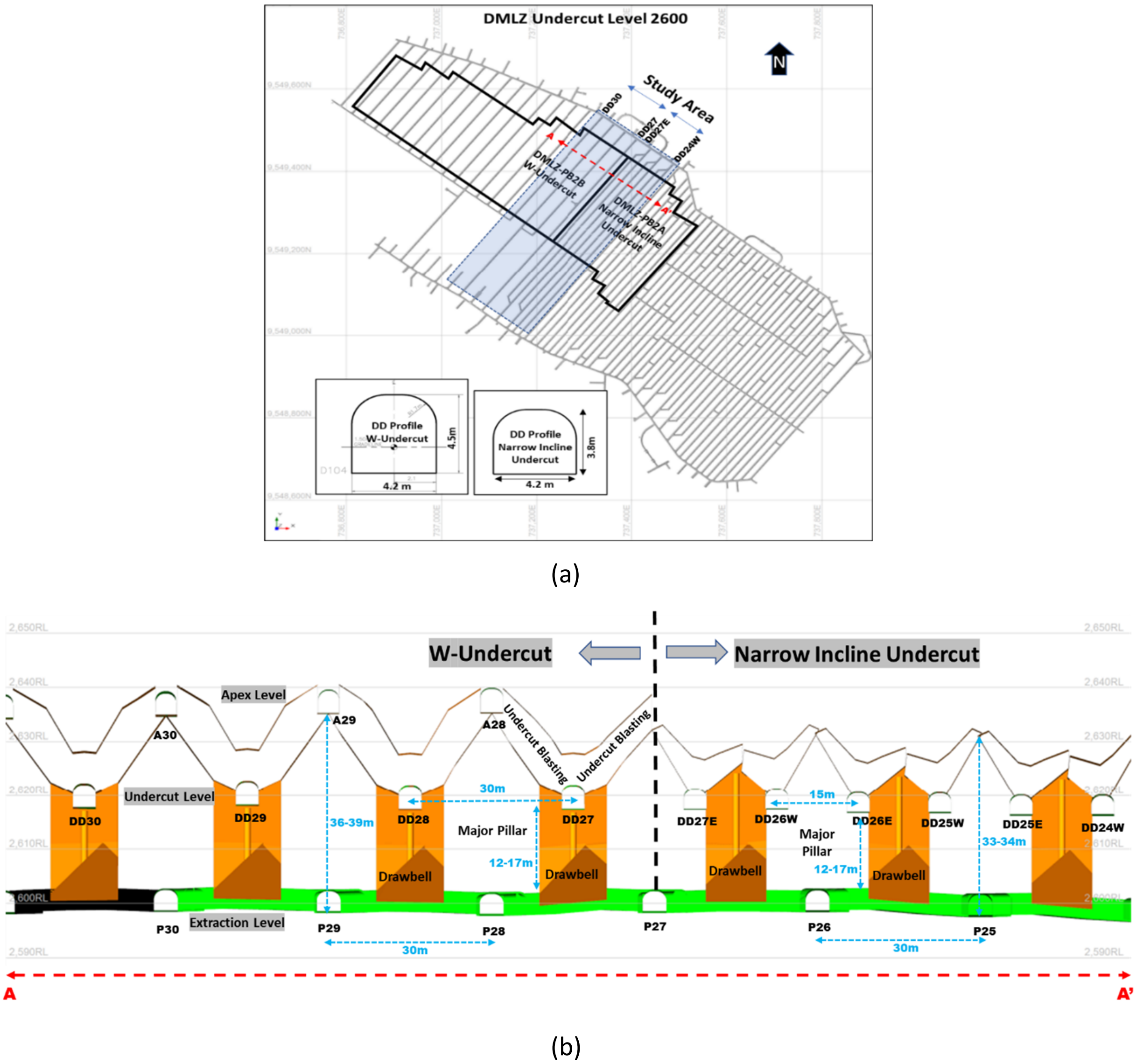


Figure 3 (a) Study area at undercut level 2600 L DMLZ-PB2; (b) Section views of the transition area narrow incline undercut to the w-undercut layout

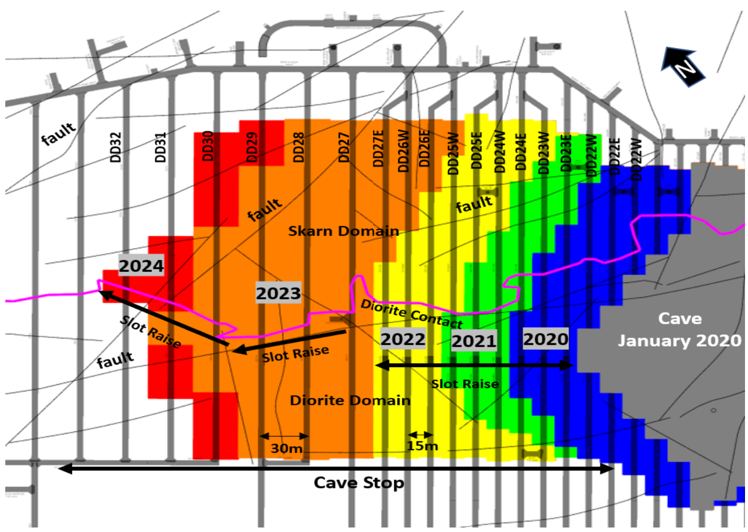


Figure 4 Undercut sequence V-shaped in DMLZ-PB2 during 2020–2024 where the slot blasting initiation follows the diorite and skarn contact

A summary of the undercut blasting performance inferred better results after the w-undercut layout was applied. Monthly square metre (m²) undercut blasting in w-undercut shows an increased trend (starting in March 2023), with the peak monthly achievement of 4,300 m² compared to the narrow incline undercut peak monthly achievement of 2,500 m². This increasing trend in w-undercut is mainly due to larger area within undercut rings (66 m²) compared to the narrow incline undercut (33 m²). The closure time for re-entry protocol activation due to seismic events has significantly decreased since the w-undercut was implemented. It has also contributed to enhancing productivity with undercut blasting. The review details are discussed in section 4.3. Along with the undercut blasting trend, the DB blasting at the extraction level also showed a slight uptrend caused by an increase in total DB inventory. The details for both the undercut and DB blasting achievements are presented in Figure 5.

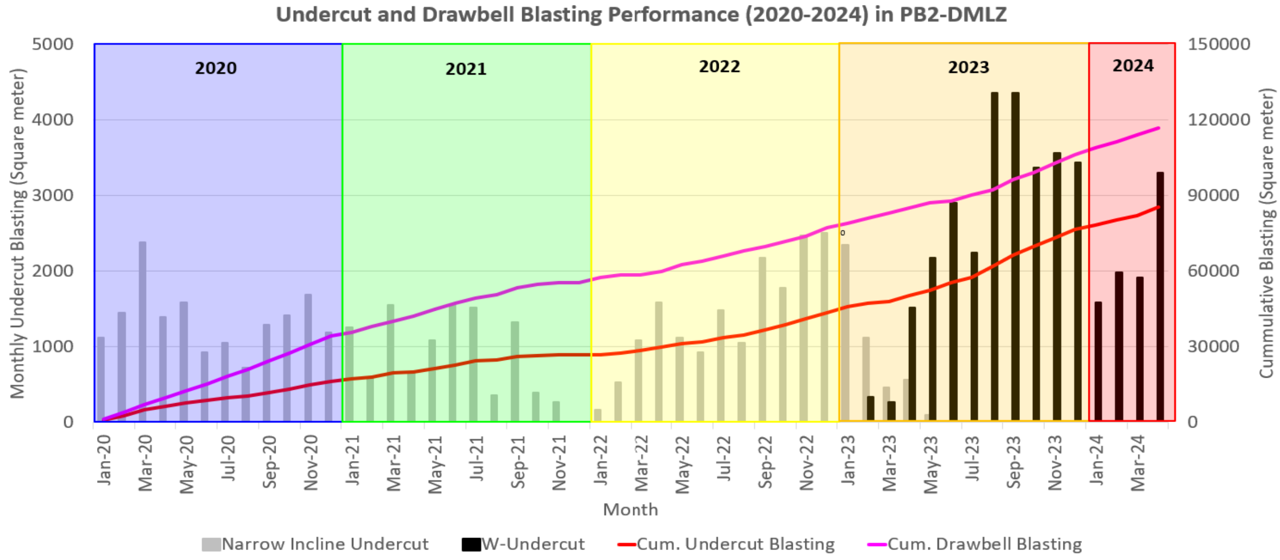


Figure 5 Undercut and drawbell blasting achievements in DMLZ-PB2 during 2020–2024

4 Geotechnical review

A comparative geotechnical review of w-undercut and narrow incline undercut layout was evaluated with consideration of several aspects that contributed as success parameters. The geotechnical aspects discussed in this section are ground response and rockburst occurrences due to cave-induced abutment loading, numerical redistribution stress and stress level index (SLI) modelling, seismicity condition in the abutment area and preventative support maintenance (PSM) installation frequency.

4.1 Ground response and rockburst occurrences

The DMLZ-PB2 area is dominantly developed in a skarn domain with the Ertsberg diorite contact along the southern boundary and sedimentary rock contact along northern boundary. Several major northeast-trending faults intersect the area, which causes local stress variances and subsequent convergence in the undercut level. A total of 877 convergence data points in the skarn domain and 196 data points in the diorite domain were evaluated in undercut level DD24E–DD27E (DMLZ-PB2) as a representative of ground deformation data in the narrow incline undercut. Meanwhile, analysis of the w-undercut layout using a total 1,379 convergence data points in the skarn domain and 396 data points in the diorite domain in DD27–DD30 was undertaken. The estimation of single-wall displacement is approximately 70% of the total wall convergence measurement. A quantitative single-wall displacement versus distance to cave was plotted in the graph to compare the ground response in the narrow incline undercut and w-undercut design.

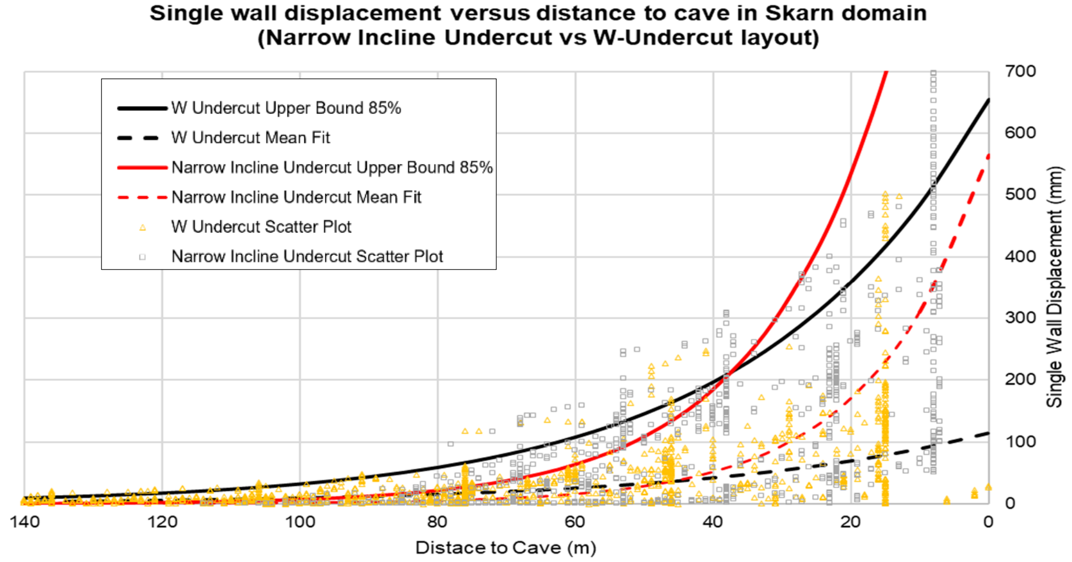


Figure 6 Single-wall displacement versus distance to cave in the skarn domain

In the skarn domain the mean fit trendline at the narrow incline undercut shows the ground displacement has exponentially increased from a 30 m distance to the cave (100 mm of displacement). The ground damage mechanism in the skarn domain is predominantly bulking that causes increased deformation. The single-wall displacement in the w-undercut is quite better compared to the narrow incline undercut as presented in Figure 6.

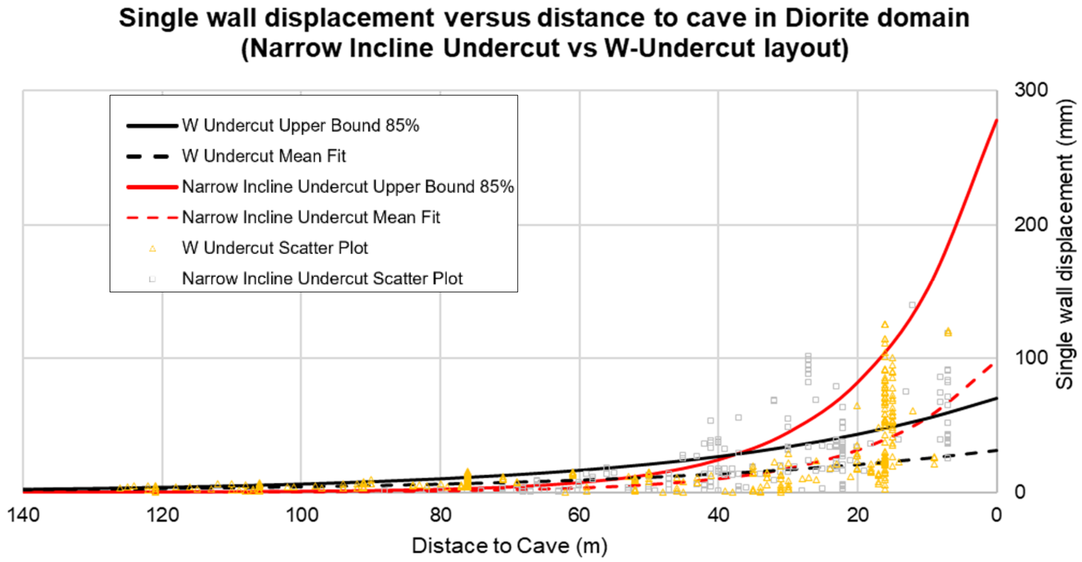


Figure 7 Single-wall displacement versus distance to cave in the diorite domain

A comparative single displacement data in the diorite domain is almost three times lower than in the skarn domain (see Figure 7). This a clear sign that the different rock mass strength and geological settings are contributing factors in distinguishing the failure mechanisms at similarly stressed locations.

In the narrow incline undercut layout the damage observed in the skarn domain occurred predominantly at the wall area, with a few occurrences at the roof (at DD24E–DD27 during 2021–2022). The majority of nine locations with back damage that indicated with shotcrete failing and bulging located near the local faults.

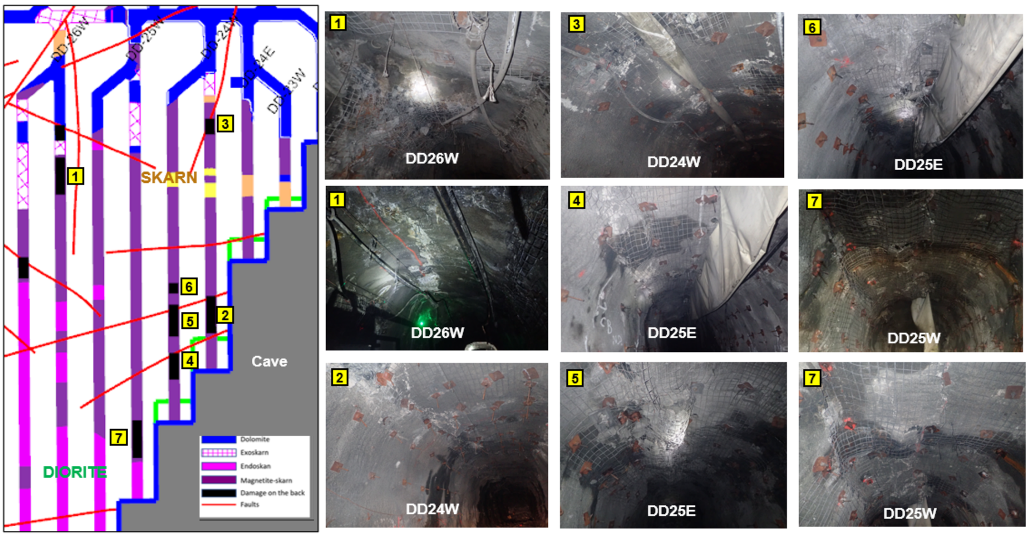
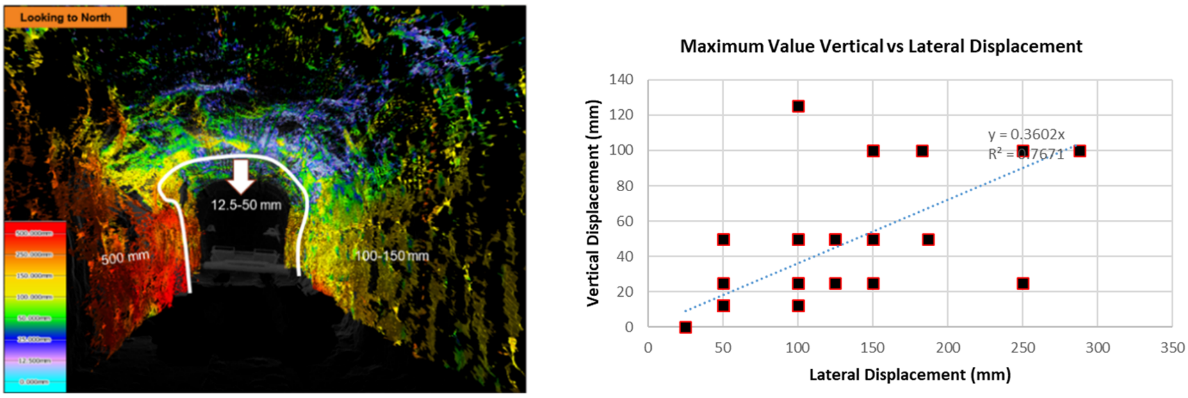


Figure 8 Visual observation of roof damage (2021–2022) overlaid with geology features in DMLZ-PB2

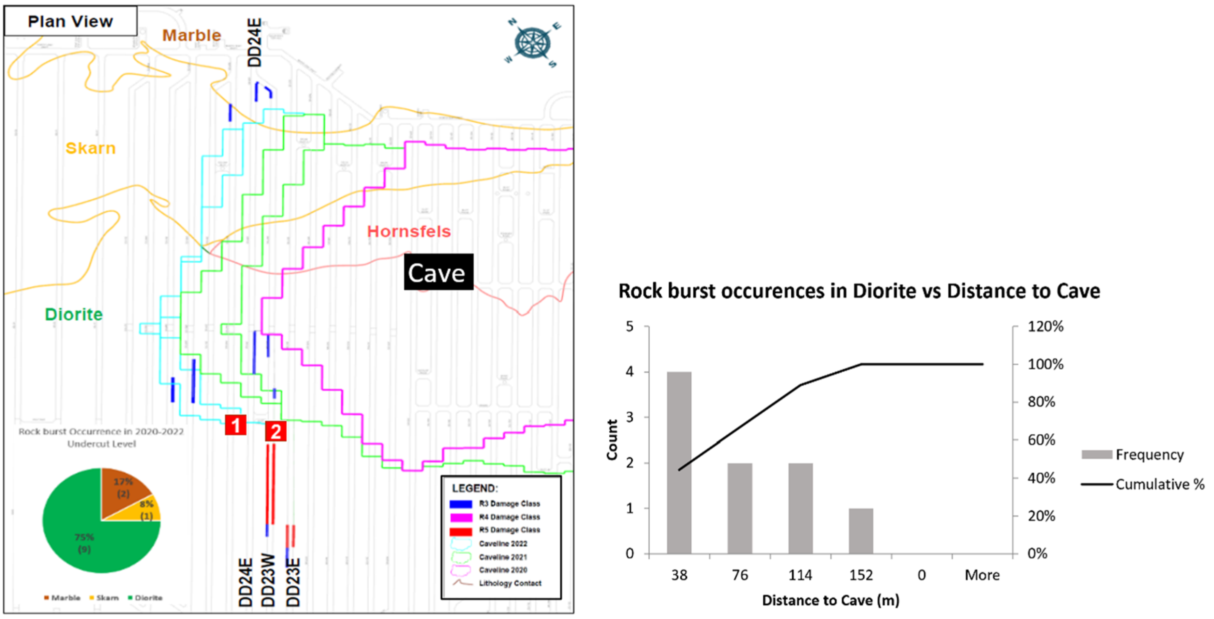
A LiDAR laser scan monitoring was carried out in DD24W to DD27 to measure the actual horizontal displacement of the wall and vertical displacement of the roof area. Figure 9a presents the scan result at DD26W that shows high displacement at the wall that also impacted the roof area. Figure 9b demonstrates good correlation between horizontal and vertical displacement. This could support the hypothesis that a reduction in effective span and the accompanied substantial displacement of the wall is linearly correlated to the tangential straining from the back, which is identified from roof displacement. The wall displaces at an average ratio of 3:1 to back displacement. Confining excessive wall displacement to prevent deformation from the backs may assist the prevention of stability loss.



(a) (b)

Figure 9 (a) A LiDAR scan result at DD26W; (b) Correlation graph of lateral displacement (wall) and vertical displacement (roof)

In undercut level DMLZ-PB2, the rockburst events dominantly occurred in diorite domain (75% of total events). The rock behaviour in the skarn domain is less burst-prone than in the diorite domain, but rather accounts for large bulking deformation due to a ductile rock mass. Cave-induced abutment loading in a massive brittle rock mass condition (diorite) was attributed to quasi-static spalling and rockburst damages. It is very likely that the load redistribution due to the blasting (undercut or DB blasting) is the trigger for the strainbursts. Rockburst events mainly occurred at distances up to 38 m from the cave line, which contributes to 40% of total rockburst occurrences (Figure 10b). All rockburst events in DMLZ-PB2 were located in the narrow incline undercut. Meanwhile, rockburst damage was not observed in the w-undercut layout. This indicated that the increasing of pillar geometry in the w-undercut layout had a good result in managing stress distribution in the abutment area.

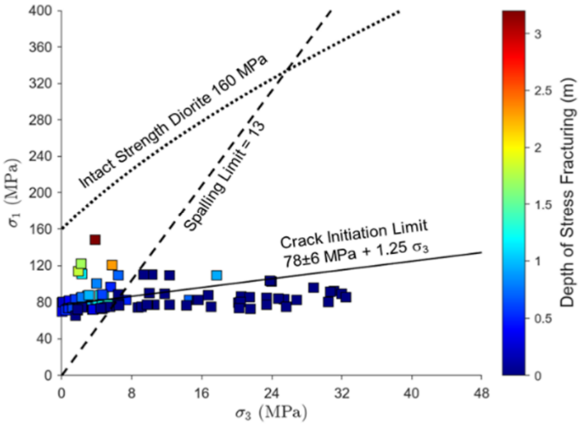


(a) (b)

Figure 10 (a) Rockburst events map at undercut level DMLZ-PB2 occurring in 2020–2022; (b) Histogram graph of rockburst frequency versus distance to cave in the diorite domain

4.2 Numerical stress modelling

The distance from the cave front is a critical geomechanical parameter where cave-induced stress influences the progression of the depth of stress fracturing (DoF) and bulking displacement as the undercut approaches the excavation development (Primadiansyah et al. 2024). The numerical 2-D finite element method was constructed using Rocscience RS2 9.0 software to simulate the excavation drift and assess its influence on stress redistribution, the DoF and pillar stability. To simulate the brittle behaviour around excavation arising from the planned development, the damage initiation and spalling limit constitutive model (Diederichs 2007) was employed. Input parameters were determined through recent calibration works in DMLZ-PB2 (Primadiansyah et al. 2024) in the diorite domain, which is presented in Figure 11.



Type	Hoek-Brown Parameters	
Elastic	E_v (GPa)	53
	v	0.25
Peak strength	m_b	0.2
	s	0.24
	a	0.5
Residual strength	m_b	12
	s	0.001
	a	1

Figure 11 Input parameters used in RS2 based on recent calibration works for DMLZ-PB2 (Primadiansyah et al. 2024) regarding crack initiation and spalling limit based on elastic stress analysis

The stress modelling in the narrow incline undercut layout was analysed with representative conditions after slot undercut blasting at DD24W (January 2021). The result shows that redistribution stress due to slot blasting and caving progresses has impacted until two DDs ahead of the cave front, with the estimated sigma 1 around 120 MPa to 160 MPa (see Figure 12). The stress interaction between the extraction and undercut level is visible at the leading major pillar/major apex panel 25.

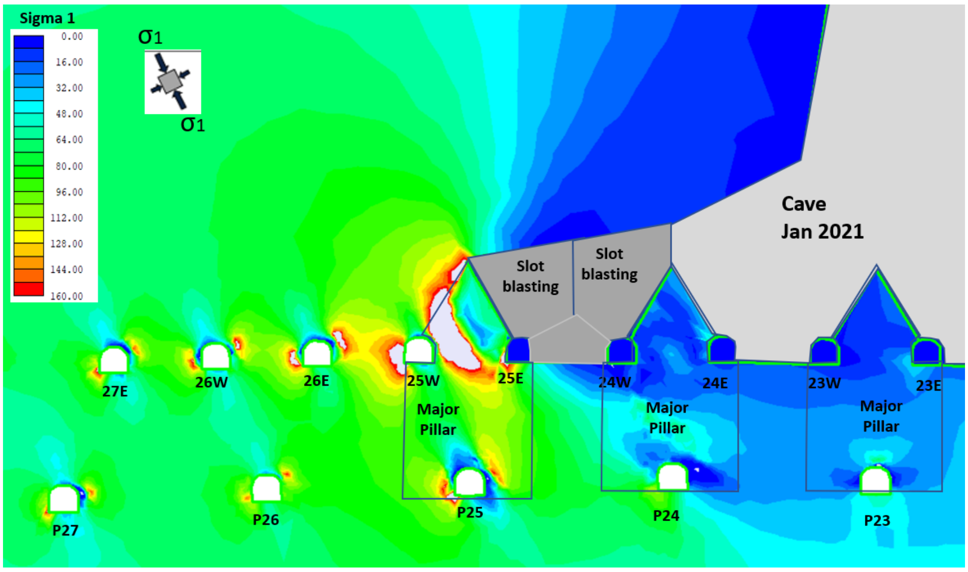


Figure 12 Model results showing estimated stress redistribution in the narrow incline undercut layout

The impact of complex stress redistribution on the progression of DoF around an excavation was evaluated based on the SLI, as adopted by Martin et al. (1999), Kaiser et al. (2000), Diederichs (2007) and Perras & Diederichs (2016). Their method is considered suitable to predict brittle failure for massive to moderately jointed rock under high SLI, which is represented in diorite rock behaviour in DMLZ-PB2. The SLI represents the ratio of maximum tangential stress (σmax) at the excavation wall to the strength of the intact rock (UCS). The UCS used for the diorite domain is 160 MPa.

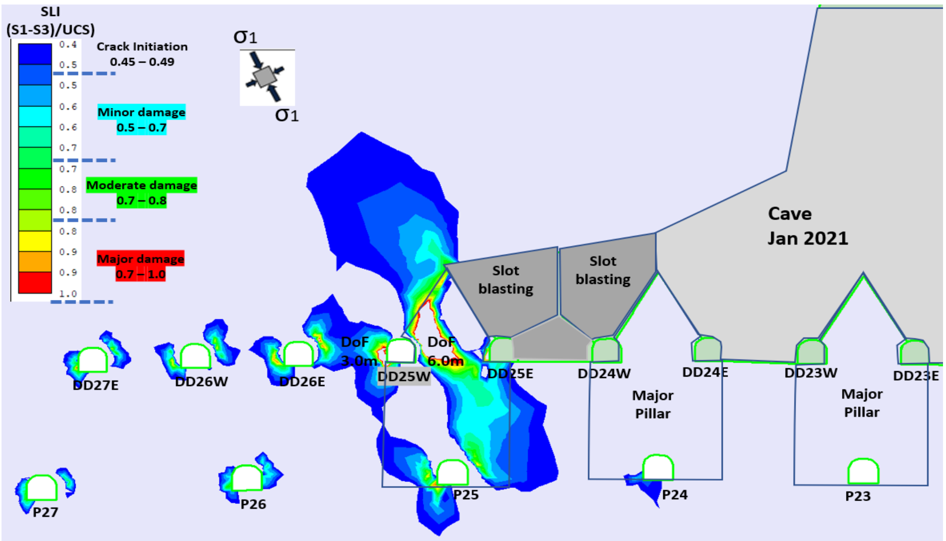


Figure 13 Model results showing the estimated depth of stress fracturing based on the stress level index in the narrow incline undercut layout

A recent study indicated that a rapid increase in the DoF shows near the SLI of 0.45–0.49 (Primadiansyah et al. 2024). Calibration of the model and actual borehole camera damage refers to a site experience in 2017 which took place in the major pillar apex. This calibration resulted in a damage threshold in the SLI of 0.59. Analysis of the narrow incline undercut layout and output from the SLI models estimate that the DoF at ahead drift from the cave front (DD25W) is around 3.0 to 6.0 m (Figure 13). Two pillars ahead of the cave front have values greater than 0.7, indicating that they will experience moderate damage. The next pillars show values between 0.5 and 0.7, indicating minor damage, however, these pillars will likely exhibit increased levels of damage as the cave advances. The major pillars represent significant elements in the control of damage on the extraction level.

Referring to a recent study from Primadiansyah et al. (2024), the estimation of single-wall displacement can be predicted by a function of tunnel strain (with displacement normalised to the effective extraction drift radius) and plotted against the DoF. The observed DoF (denoted as R_f and measured from the centre of the circumscribed circle of the excavation) has been normalised to the effective or equivalent extraction drift radius of 2.6 m. Figure 14 Illustrates the definition of the two fractures.

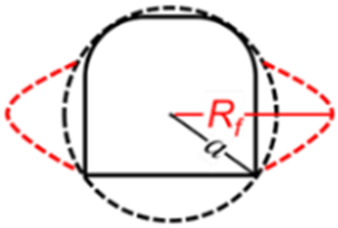


Figure 14 Illustration of the observed depth of stress fracturing (R_f) normalised to the effective or equivalent extraction drift radius (a)

The single-wall displacement can be calculated as:

$$Displacement = a\ x \left(\frac{\ln\left(\frac{\frac{R_f}{a}}{1.07}\right)}{10} \right) \tag{1}$$

Based on the DoF estimation from the model at ahead drift from the cave front (DD25W) approximating 3.0 to 6.0 m, the prediction of single-wall displacement is around 160 to 280 mm. The displacement was confirmed by an actual LiDAR survey, which indicated a cumulative wall displacement of around 150–250 mm for the left wall and more than 250 mm at the right wall. The LiDAR survey results in DD25W are presented in Figure 15.

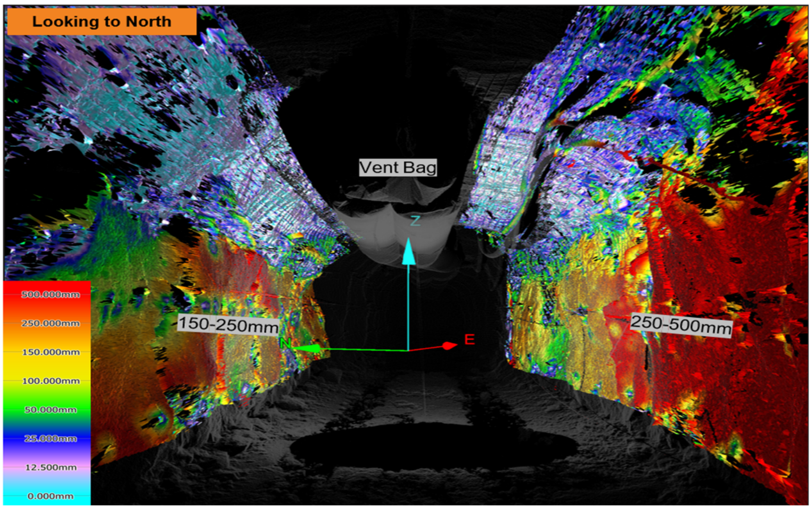


Figure 15 The LiDAR survey result at DD25W shows 150–250 mm (left wall) and 250–500 mm (right wall)

The transition to the w-undercut layout was also modelled to determine the redistribution stress and DoF with the actual representative condition after slot undercut apex blasting at DD27 and DD28 (February to March 2023). The impact of redistribution stress reached just one DD and apex drift ahead from the cave front with estimated sigma 1 of around 100–160 MPa (see Figure 16). Increasing the size of the pillar in the w-undercut layout has improved ground conditions. The stress interaction between the extraction and undercut level also indicated less stress than the narrow incline undercut layout at the leading major pillar.

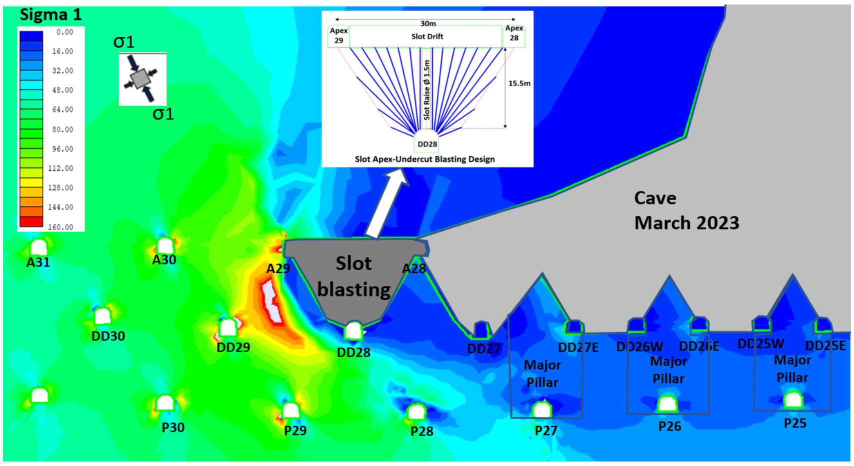


Figure 16 Model results showing estimated stress redistribution in the w-undercut layout

The SLI models for transitioning to w-undercut layout estimate that the DoF at ahead drift with the cave front (DD29W) was around 2.0–4.0 m which can be seen in Figure 17. Lower damage values show in the leading pillars compared to results in the narrow incline undercut. Also, a more favourable stress interaction between the extraction and undercut levels is evident.

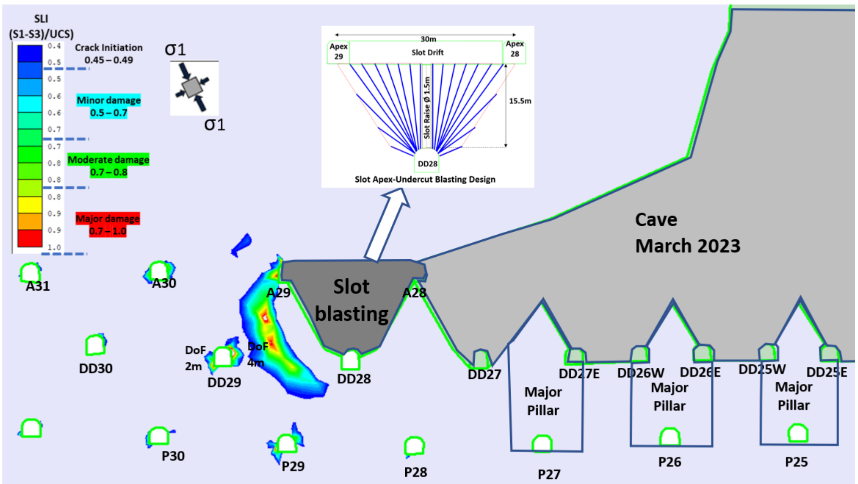


Figure 17 Model results showing estimated DoF based on stress level index in the w-undercut layout

Based on the estimate of the DoF at ahead drift from the cave front (DD29) of 2.0–4.0 m, the single-wall displacement was predicted at around 105–205 mm. This displacement was confirmed by an actual LiDAR survey conducted at DD29 which shows a cumulative wall displacement of around 50–100 mm (left wall) and 75–150 mm (right wall). The LiDAR survey result in DD29 is presented in Figure 18.

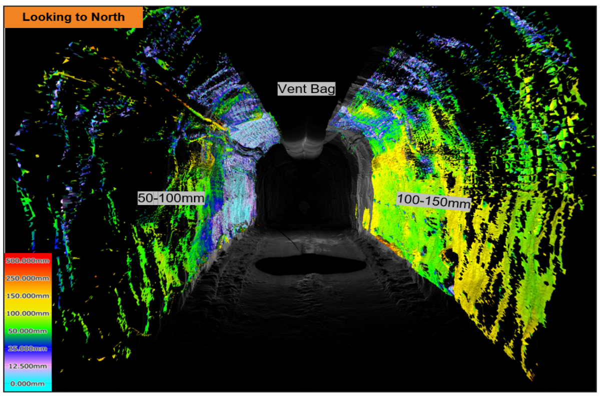


Figure 18 The LiDAR survey result at DD29 shows 50–100 mm (left wall) and 75–150 mm (right wall)

4.3 Seismicity evaluation

As cave progressed in the DMLZ mine, cave-induced stresses were realised in the abutments, resulting in more spalling developing around the drifts and rockburst damages. The highlight from a study by Roy et al. (2023) shows that 80% of the rockburst damage (in linear metres) was associated with seismic events occurring between 50 and 60 m from the cave front. This is an indication of strainbursting being the dominant rockbursting mechanism in the DMLZ.

Figure 19 presents the magnitude-time seismic events and cumulative apparent volume (CAV) in the abutment area with a boundary of 50 m above and below the undercut level. This graph overlays with the rockburst events at the undercut level in DMLZ-PB2 and source mechanism analysis. Based on the Hudson et al. (1989) plot, the seismic source mechanism in the rockburst events period predominantly showed a closure/crushing/compressive crack mechanism. It indicated that some of the rockbursting which occurred was associated with large-magnitude seismic events.

Generally, transition to a w-undercut shows positive results in term of the seismicity parameter. In both the skarn and diorite domains, DMLZ-PB2 shows a trend in decreased seismic rate and significant magnitude (Mw ≥ 1.0) events after w-undercut design was implemented. The CAV also indicated a flat trend after transition to the w-undercut layout, which correlated with an absence of rockburst damage in 2023–2024. Source mechanism analysis showed no notable indication of a compressive crack mechanism (rockburst/pillarburst) in the skarn domain after the w-undercut was applied. Meanwhile, the diorite domain predominantly with a compressive crack and shear mechanism.

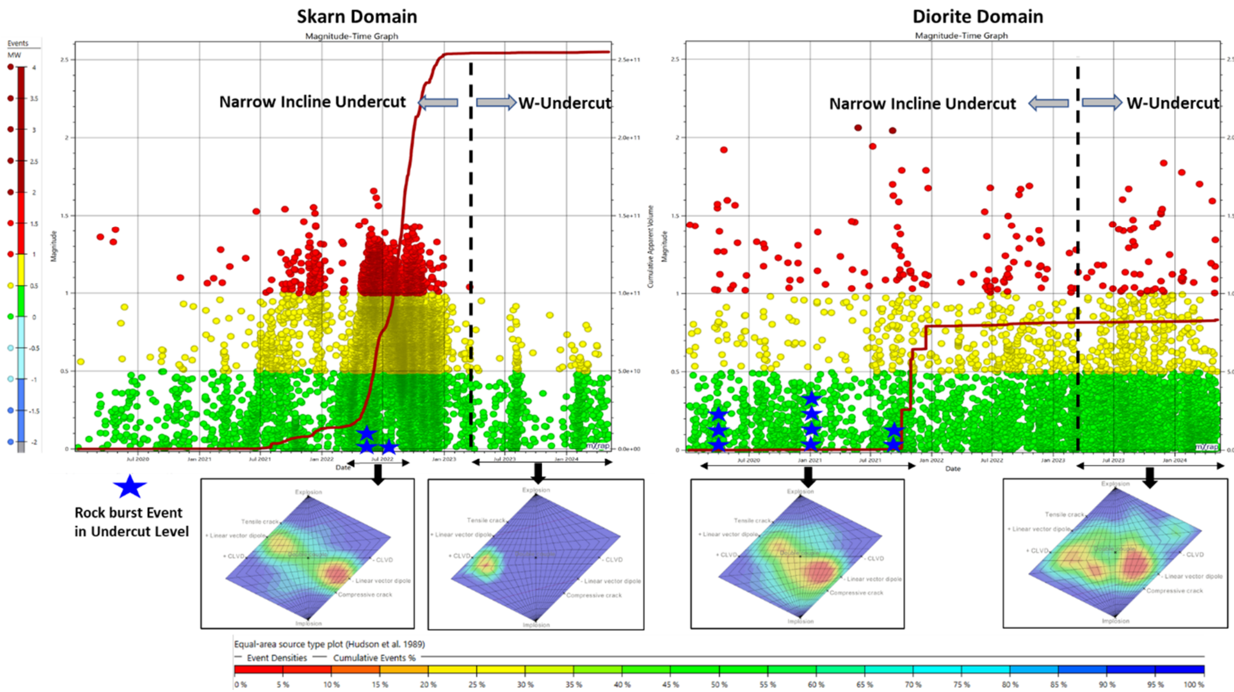


Figure 19 Graph of magnitude-time seismic events and cumulative apparent volume during 2020–2024 in DMLZ-PB2 skarn and diorite domains, overlaid with rockburst events in undercut level PB2 and source mechanism analysis using the Hudson plot

Figure 20 demonstrates the evolution of seismic propagation in the abutment cave area during 2021–2024. The iso-density of seismic events in 2021–2022 shows a bigger concentration than in 2023–2024 (w-undercut implemented). The high density of seismic events has impacted until six to seven DDs ahead from the cave front in 2021–2022 and just three to four DDs in 2023–2024.

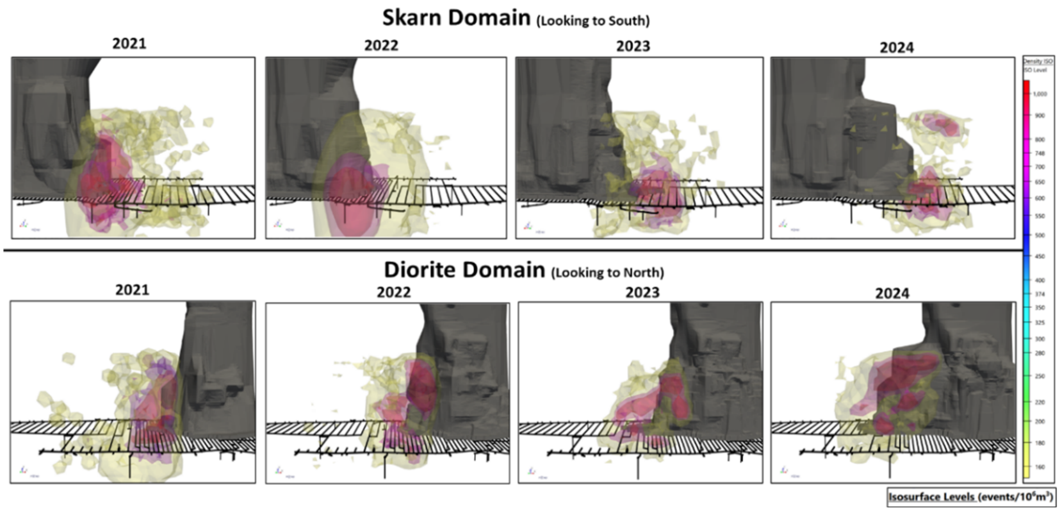
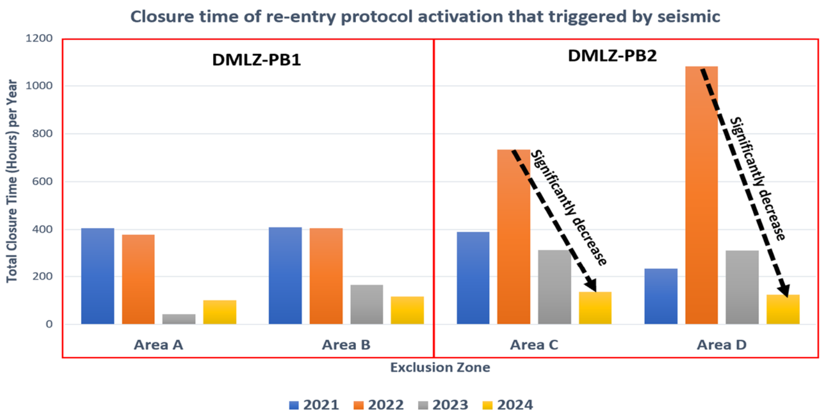


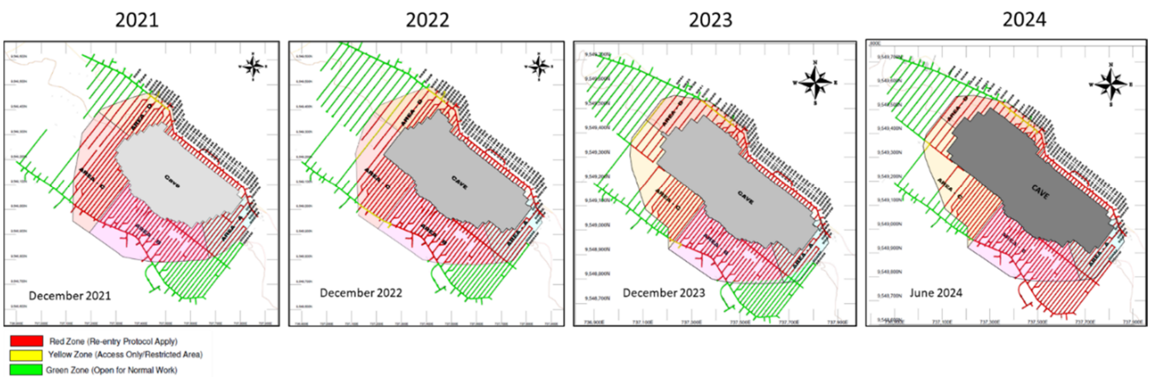
Figure 20 Iso-density of seismic events at the cave abutment area during 2021–2024

A seismic re-entry protocol was implemented to make sure all the employees can work safely in a specific exclusion zone around the cave abutment area. The activation of protocol was triggered by several parameters, including undercut and DB blasting, the seismic level index, and the seismic magnitude which exceeded the threshold. Closure duration protocol depends on the seismic category level.



Category	Parameter	Closure Durations in Concern Area (hours)
2	Seismic Level Index	until level index decrease (min 2.5)
3	1.0 ≤ Magnitude < 2.0	2.5
4	2.0 ≤ Magnitude < 2.5	until seismic parameter decreasing (min 24)
5	Magnitude ≥ 2.5	until seismic parameter decreasing (min 24)

(a)



(b)

Figure 21 (a) Total closure time triggered by the seismic index and magnitude; (b) Re-entry protocol map in undercut level with specific exclusion zone

In DMLZ-PB2 area (exclusion zones C and D), the total closure time due to seismic index and magnitude was significantly decreased in 2023–2024 (after the w-undercut was implemented). This indicated that less stress interaction in the pillar (larger size) has led to less stress fracturing-induced seismicity in abutment loading area. Pre-conditioning with hydrofracking and good strategy to improve the cave shape (uniform mucking and undercut blasting sequences) also contribute to decrease the seismic events. Less closure time will enhance productivity of drift development, undercut and DB blasting, and mucking activities.

4.4 Support maintenance evaluation

Deformation or displacement is a reliable parameter that can measure the ground response to mining and is a key reference for decision-making and planning. Maintaining ground support capacity leads to a decrease in the amount of support rehabilitation required, further reducing, or even significantly minimising, the strainburst hazard. Based on this concept, DMLZ mine adopted a staged ground support approach (PSM) (Simanjuntak et al. 2020). Figure 22 presenters parameters for the default PSM concept and ground support scheme.

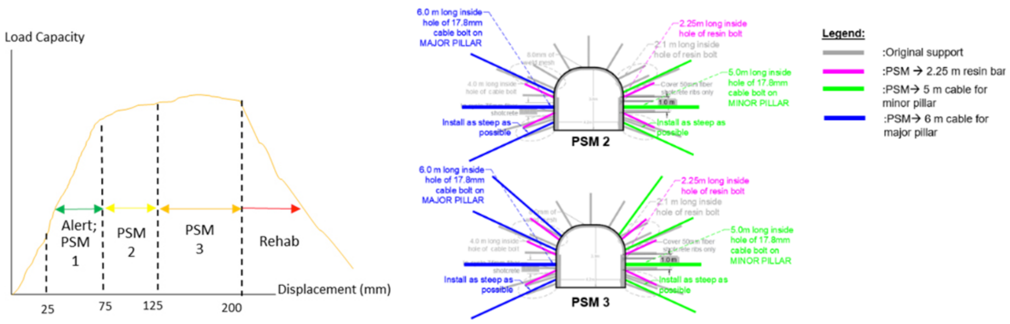
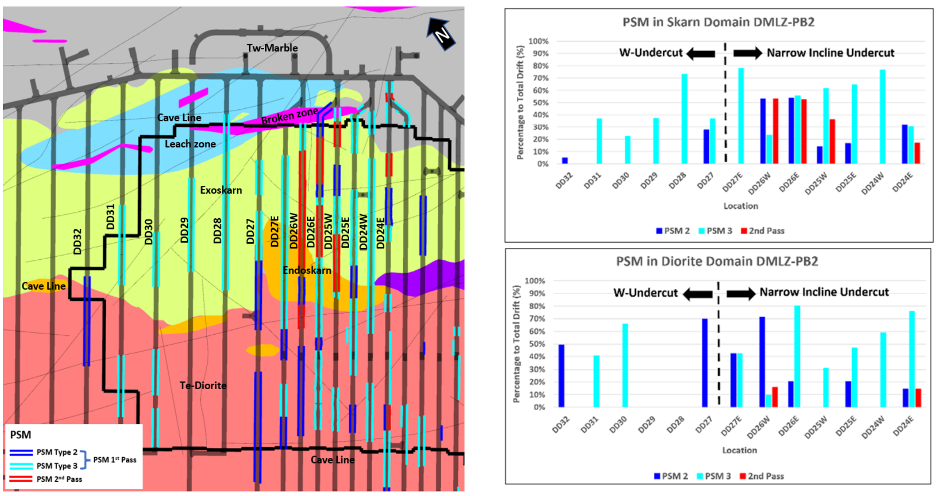


Figure 22 The default preventative support maintenance concept and ground support scheme

The distribution of PSM installation history in the skarn and diorite domains during 2021 to 2024 at undercut level DMLZ-PB2 is shown in Figure 23a. Large deformation occurred in DD24E–DD26W and it has undergone a second pass of PSM. More than 50% of the total drift in DD24E–DD26W of the skarn domain has been installed PSM (see Figure 23b) with a total of 851 linear metres (all PSM types). The second pass PSM in the diorite domain just occurred in DD24E and DD26W, with a percentage of no more than 20% of total drift. Transition to a w-undercut layout gives positive results in terms of ground response to cave and damage occurrence, which is evidenced in the PSM installation in DD27–DD32 that shows low intensity compared to the narrow incline undercut. No DDs in the w-undercut indicated second pass PSM installation.



(a) (b)

Figure 23 (a) Preventative support maintenance installation map (2021–2024) at undercut level DMLZ-PB2; (b) Percentage of preventative support maintenance installation per drill drive for the skarn and diorite domains

5 Conclusion

The adoption of the w-undercut layout was an effective way of reducing potential geotechnical hazard. Increasing the size of the pillars effectively resulted in a lower stress environment that is directly related to the minimising and management of geotechnical hazards such as rockbursts and high deformation.

The positive results that were observed during the transition from a narrow incline undercut to a w-undercut indicated that a more stable environment was created regarding drift wall displacements, with a decrease in seismicity and rockburst damages, a significant decrease in closure time seismic re-entry protocol, and a reduction in PSM requirements. This safer undercutting option also showed an increase in undercut and DB blasting achievement.

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