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Practical application of deformation-based support design

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Abstract

Panel cave mines at PT Freeport Indonesia experience damaging strainburst events due to high caving-induced stress and brittle rock mass conditions. Traditional energy-based support design principles did not provide an appropriate ground support design to manage the strainburst hazard in the mining environment. While field fitting of gabion-based support systems was successfully developed, a clear design basis was lacking. To address this gap, a deformation-based support design methodology was defined, which has proven more effective at informing support strategy under these challenging conditions. This operational change in methodology necessitated an update of the ground support design basis and supporting tools. Three significant updates to the existing load-based and energy-based design philosophy were required: 1) determine a support system capacity from individual support elements, 2) include displacement-based demand calculations in the strainburst support assessment, and 3) estimate the service life of the support system based on the anticipated loading path. Experience around the development and validation of a deformation-based support design workflow as well as challenges of implementing deformation-based support design at scale are described.

Keywords: *ground support, deformation-based support design, strainburst*

1 Introduction

Ground support installed in panel cave mines at PT Freeport Indonesia (PTFI) did not perform as expected from the initial designs developed during study phases. Support systems were unable to resist dynamic demands imposed by the evolving cave abutment throughout the extraction and undercut levels. PTFI implemented a deformation-based approach to managing ground support and successfully introduced Preventative Support Maintenance (PSM) principles in the production areas (Simanjuntak et al. 2020). By installing fresh support elements and restoring the capacity of the system, critical drifts required for cave development and production ramp-up remained available to operations.

The approach has been applied to two active caving operations: the Deep Mill Level Zone (DMLZ) and Grasberg Block Cave (GBC). The DMLZ started using PSM to improve the resiliency of the support system to damaging strainburst events. Later, this support management approach proved valuable for the GBC where strainbursting poses less of a risk to footprint stability, but the ratio of transient stress to rock mass strength is high, resulting in significant deformation.

While PSM was being implemented at an operational level supported by strong empirical guidance, the strategic and mid-term design process did not accommodate the new approach to managing ground support with PSM. At PTFI, all new development is managed through a multi-staged Plan of Intent (POI) system where geotechnical engineers contribute support designs and approve the planned development. At the time of PSM implementation at the mines, ground support designs were still based on the highest anticipated load and energy demands for the dynamic peak loading conditions, and stated support element capacities from supplier specifications and testings. Factors of safety calculated under these peak conditions suggested that the ground support design should survive the life-of-mine demand, however it did not. Significant updates to the ground support design philosophy were required to capture the realities of support performance:

1. A support system can have a larger capacity than the individual elements that make up the system (Cai & Kaiser 2018).
2. Support system capacity decreases (i.e. its capacity is consumed) as the excavation deforms in response to growing demand, and displacements must be an input to design assessments in dynamic conditions (Kaiser & Moss 2021).
3. A single ground support system cannot survive repeated peak demands and additional support is required to maintain the integrity of the excavation (Moss & Kaiser 2021).

This paper describes PTFI's updated ground support design philosophy and supporting methodology with a focus on strainbursting that takes deformation-based design principles and applies them in practice.

2 Ground support philosophy

PTFI's ground support design philosophy is based on the concept of deformation-based support design (DBSD) as recently described in Kaiser & Moss (2021). This DBSD approach was developed with the authors and determines the capacity of a ground support system based on imposed displacements. Mining-induced deformation then consumes part of this support capacity which reduces the ability of an excavation to withstand static and dynamic demands. DBSD is particularly relevant in areas where transient demand, often very high, is placed on excavations and ground support systems. Further description of the DBSD philosophy is offered in Kaiser & Moss (2021):

> *'The design has to respect that, at any point of the support's life, the remnant support capacity is less than the installed capacity. In other words, the actual factor of safety is gradually lowered by displacements imposed by mining and rockbursting. Excavations become less safe with 'time' due to this displacement-related support capacity decay. From a safety assessment perspective, it is not of interest what the capacity of the support is or was at the time of installation, rather it is necessary to establish the 'current' factor of safety and to maintain sufficient capacity when needed. Particularly in yielding and brittle fractured ground, the design must account for deformation-based support capacity consumption.'*

2.1 Preventative support maintenance

The DBSD approach states 'if support capacity can be consumed, it can also be restored' (Kaiser & Moss 2021). Surface and tendon ground support can be impacted by ground movement, equipment damage and corrosion/sulphate attack. Where such conditions are identified, and the ground support capacity has not been completely exhausted, PSM is utilised to proactively replenish the lost ground support capacity.

Regular observation, measurement and good record keeping is critical to the successful implementation of PSM. Monitoring of displacement, corrosion and equipment-induced support damage is conducted regularly in order to inform where and when PSM may be required. Geotechnical engineers provide maps of PSM locations, support specifications, and priorities to mine engineering and operations to manage PSM installation (Figure 1). Where PSM is insufficient to maintain a safe working environment, more aggressive rehabilitation such as rib slashing and full re-support may be required to maintain a safe excavation.

PSM is sensitive to the timing of support remediation. Excessive delay in PSM installation may compromise the load, displacement and energy capacities of the ground support system before the support upgrades are completed. The schedules and stated thresholds for PSM have been empirically determined such that support upgrades can be made while support system capacity remains within the required acceptance criteria. If the measured displacement in an excavation exceeds a given threshold (typically 75 or 125 mm) without any additional support, the area is barricaded until PSM is complete. Napitupulu et al. (2022) presents a comprehensive overview of PSM practices at DMLZ.

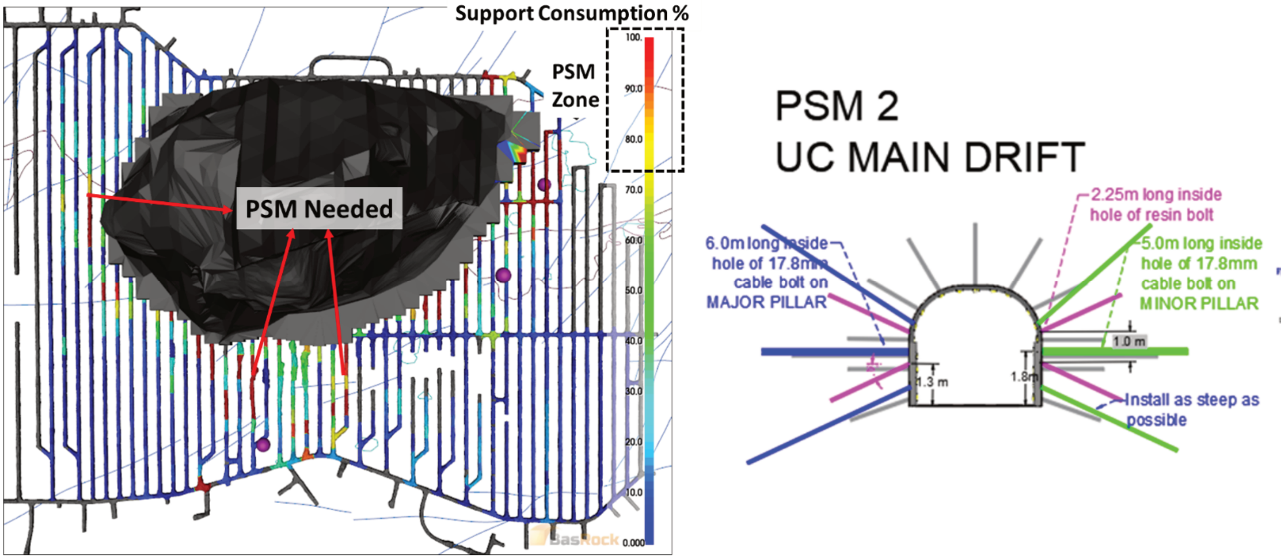


Figure 1 Ground support consumption heat map and support specification for PSM on the undercut level (modified from Simanjuntak et al. 2020)

2.2 Acceptance criteria

PTFI considers the usage, occupancy and exposure of an excavation to determine the acceptance criteria used for design. The occupancy rate is based on the number of people that may be in or pass through any excavation within a given period. Classifying all areas into zones assists in setting schedules and frequencies for regular ground support and rock condition inspections that will be carried out for all accessible underground areas. Each zone has stated static and dynamic factors of safety (FoS) against which the design is evaluated.

An acceptable ground support design does not need to meet the acceptance criteria for the maximum anticipated demand over the life of the excavation. Because of the monitoring data collected and PSM philosophy, additional ground support may be installed when the support system capacity drops below the required levels to protect against future demand events. The goal of the ground support design is to evaluate whether a support system in the planned excavation is expected to survive peak demand, and if not, identify the future date (via mining stage) when PSM is anticipated.

3 Ground support design workflow

The demand and capacity assessments for ground support design are conducted using PTFI's Ground Support Scoping Tool (GSST). The GSST is an auditable spreadsheet that incorporates several semi-empirical methods into one tool. The GSST methodology is designed to provide guidance for an initial selection of support system components and systems, and provides the framework for an iterative evaluation of the design. It also plots estimated demands versus capacity over a full life-of-mine stress path and calculates FoS and remnant FoS for load, displacement and energy. Specifically, the tool allows for rapid empirical checks for the following excavation failure mechanisms:

- Kinematic (structural) instability.
- Brittle/spalling failure.
- Dynamic failure (e.g. bursting).
- Squeezing failure.

Demand is derived from a combination of rock mass and stress conditions. The stress path is forecast based on published development, undercutting, and draw schedules. Specifically, the anticipated loading (stress) conditions considered for support design are estimated from the results of a mine-wide stress model completed by Beck Engineering (Figure 2). From these simulations, a stress tensor database is developed, and used as inputs to define per-mining stage demand for ground support design. Queried model results near the design excavation are input into the Kirsch equations to calculate the anticipated stress at the excavation boundaries. For most of the planned excavations, the 'worst-case' stress conditions are not the pre-mining stress but rather the abutment zone stress.

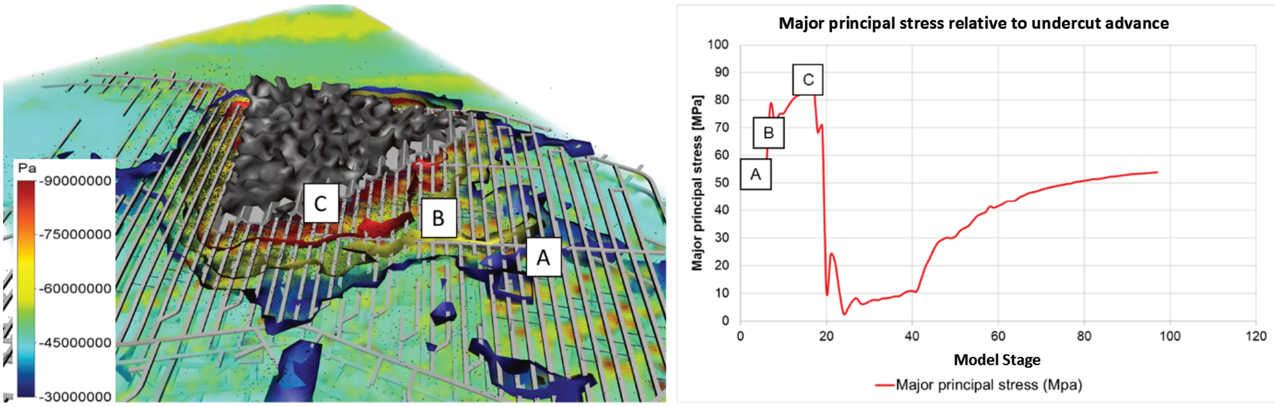


Figure 2 Maximum principal stress modelled in the DMLZ showing changing loads during undercutting (i.e. advancing model stages) (Simanjuntak et al. 2020)

Rock mass characteristics are derived from characterisation reports and compared against local drillhole and geotechnical block model data to determine the appropriate ground type for design: Very Poor, Poor, Good, and Very Good (Laubscher 1990). Rock mass characteristics and stress conditions are combined to determine the ground support category and associated failure mechanisms as described by Kaiser et al. (2000). These mechanisms can be categorised into four primary modes of failure; static, squeezing (quasi-static), dynamic, and gravity failure (loss of confinement). Figure 3 illustrates the four primary failure mechanisms observed at PTFI.

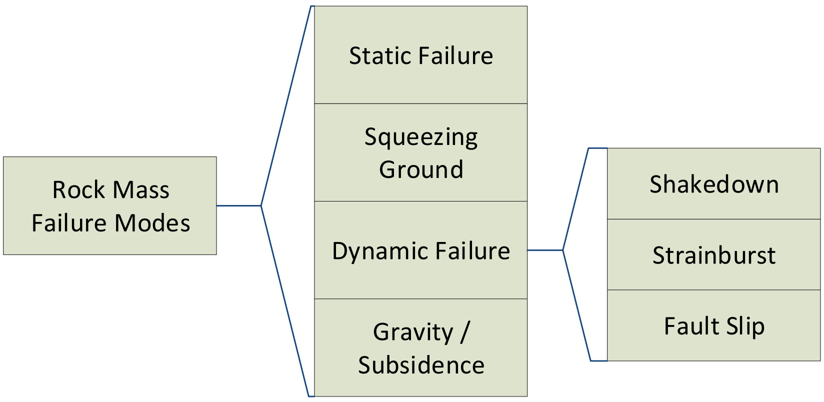


Figure 3 Assessed rock mass failure modes at PTFI

Based on the demand estimation, a ground support system is then selected that has the capacity to withstand the calculated demand on the excavation during the pre-peak and peak loading stages. Support System Capacity (SSC) calculations must demonstrate that the support components are of an appropriate length, spacing, deformability and strength to determine the adequacy of the designed support system. The methodology described by Kaiser & Moss (2021) is used to calculate the SSC from individual elements. Where demand is expected to exceed the SSC, guidance is issued to clearly indicate when in the excavation life additional ground support must be installed to incrementally restore SSC. Convergence and LiDAR scan measurements are the control measures used to track transient SSC within mine excavations.

Demand and capacity calculations consider the defined acceptance criteria, guided by the purpose and life span of the excavation, as well as the expected levels of personnel exposure/occupancy. These FoS are determined for each stage in the stress path.

3.1 Worked example

The following design example is for a panel drive excavation in the DMLZ.

3.1.1 Demand

Demand is treated as a combination of different static and dynamic demand sources. The first step is to determine those individual elements of the combined demand imposed on the design.

3.1.1.1 Stress path and loading

Figure 4 shows the local loading path for the design assessment. Note four important demand stages are considered:

- Stage 0: Initial loading stage.
- Stage 9: Pre-failure loading stage.
- Stage 10: Post-failure stage.
- Stage 15: Peak loading stage.

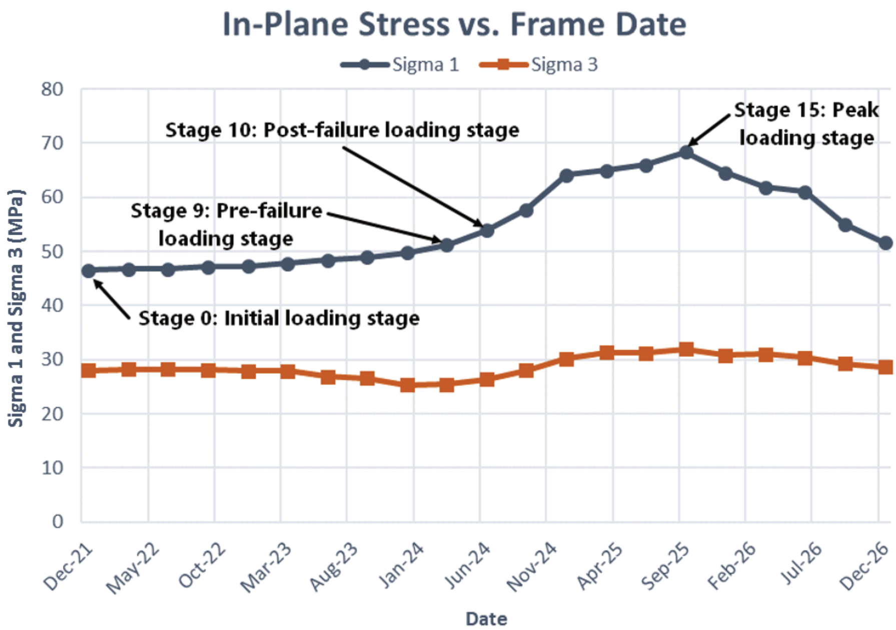


Figure 4 Sigma 1 and Sigma 3 in-plane for a selected loading path

DMLZ intact rock strength in the cave and footprint areas is Very Strong (100–250 MPa), with a representative strength of 160 MPa. The rock mass is massive with very few open joints (<1 per metre). Veins form the primary rock fabric. The combination of the stress inputs and rock mass characteristics indicate a high stress ratio (σ_1/σ_3) and stress to strength ratio, where brittle failure (spalling) of the intact rock surrounding the excavation is anticipated.

3.1.1.2 Static demand

Diederichs & Martin (2010) provides the estimation of the spalling depth of failure in the back and ribs of an excavation based on the equivalent excavation radius, maximum principal stress, and spalling initiation threshold. Static displacement is then calculated from the depth of failure and a user-selected static bulking factor for a single rib of the excavation (Kaiser et al. 1996).

3.1.1.3 Dynamic demand

Depending on the rock mass characteristics (e.g. geological strength index (GSI), unconfined compressive strength (UCS)), stress, and local geologic conditions, dynamic assessment may not be applicable to a given design scenario. For the purposes of this example, it is assumed that dynamic conditions are present.

The dynamic ground support design assesses the dynamic load, displacement, and energy associated with bulking with ejection (strainburst) and shakedown. The inputs to the dynamic assessment build off the static assessment calculation and use a parametric assessment of three different strainburst demand cases – Lower, Mid, and Upper – to give the design engineer a range of possible conditions. In the design methodology, the Mid-size strainburst event is evaluated against the acceptance criteria.

The strainburst depth is an additional fracture zone triggered by the stress wave from a seismic event which increases the overall static depth of failure. It is assumed in the ground support design calculations that the strainburst depth is a function of the initial static depth of failure. The strainburst depth is calculated as follows:

- Lower: 0.25 × static depth of failure with a minimum depth of 0.5 m.
- Mid: 0.5 × static depth of failure with a minimum depth of 1.0 m.
- Upper: 1.0 × static depth of failure with a minimum depth of 2.0 m.

The maximum strainburst depth is constrained by the excavation dimensions (e.g. in a 4.4 m wide by 4.0 m high drift, the maximum strainburst depth in the rib is assumed to be 4.0 m). This assumption on the maximum depth and the constants in the equations to determine the minimum depth (e.g. 0.25 times the static depth of failure with a minimum of 0.5 m for the lower-size event) are estimates based on a series of observations on static depth of failure and strainburst experiences in DMLZ to date. Further calibration of these formulas is in progress to better define probabilities of occurrence for these values.

The strainburst bulking factor (BF_{sb}) increases beyond the static bulking factor due to shaking from the seismic event and produces a dynamic displacement (δ_d). The dynamic bulking factor inputs currently range from 2.5% to 7.5% to represent different strainburst events. Dynamic bulking displacements are calculated from the strainburst depth of failure and strainburst bulking factor for the back, rib, and floor areas. Ultimately, the total strainburst depth is a combination of the static and dynamic depths of failure.

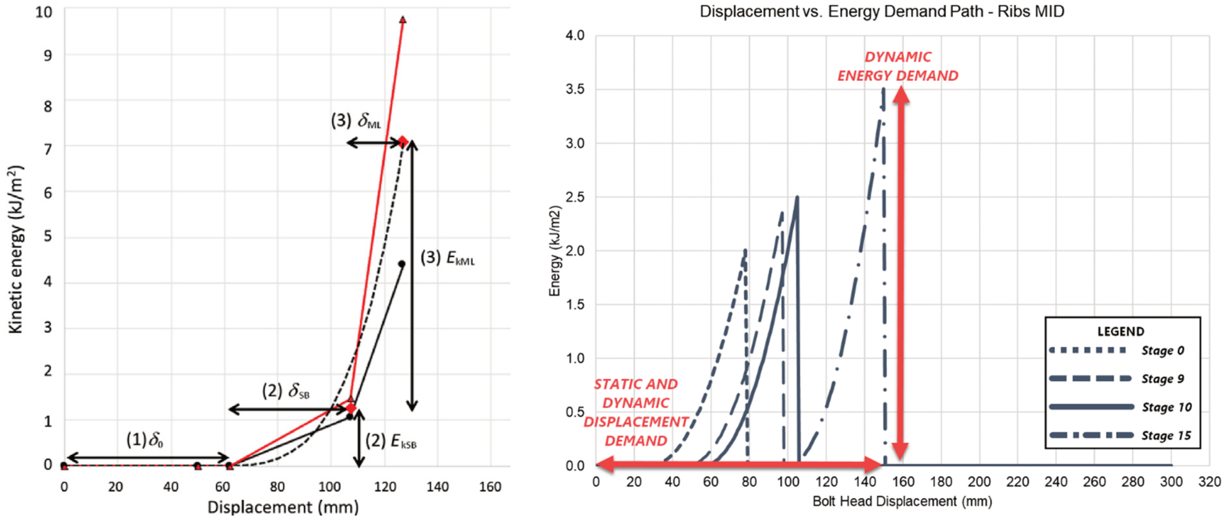
Strainburst energy is calculated for the back, ribs, and floor as a function of the ejection mass and ejection velocity using the equations described in Kaiser et al. (1996). The average velocity of the full strainburst volume is assumed to be half of the maximum velocity at the inside of the burst volume.

3.1.1.4 Combined demand

Kaiser & Moss (2021) presents the demand on the support system as a combination of different static and dynamic sources to best capture the overall demand on the system. Figure 5(a) illustrates a conceptual case where energy and displacement demands are added from three sources: static displacement (1), dynamic displacement and energy demand from a strainburst event (2), and additional energy and displacement demand from a remote event (3). During the design process, these curves are calculated and plotted per mining stage to compare against the remnant support system capacity. Figure 5(b) shows four demand curves calculated for four stages of the worked example, specifically highlighting three important stages of the stress path.

In Figure 5(a), the third demand component from a remote seismic event is not considered relevant for PTFI and not included in the Energy-Displacement curve. This third type of demand occurs when larger, fault slip type seismic events occur at a remote distance away from an excavation and induce a rockburst (Kaiser et al.

1996; Morissette et al. 2012). Bursting events observed at PTFI are linked to lower magnitude, typically less than local magnitude 2, locally damaging strainburst events.

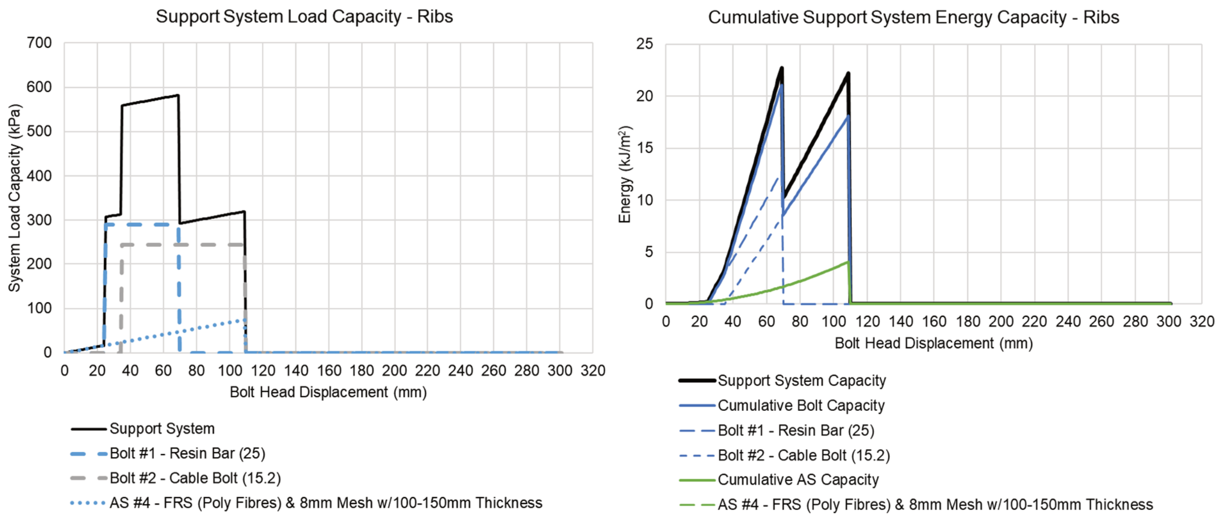


(a) (b)

Figure 5 Energy versus displacement for three individual demand events (Kaiser & Moss 2021) (a); and displacement versus energy demand path for the worked example showing Stages 0, 9, 10, and 15 (b)

3.1.2 Capacity

Ground support system capacity is calculated from the methodology described in Kaiser & Moss (2021). SSC is estimated from the individual support components, both tendon and areal support. The load-displacement curves for the individual elements are added to create a total load-displacement curve for the support system (Figure 6a). The area under the load-displacement curve is used to calculate the energy or work done by the support system over the range of imposed displacements (Figure 6b).



(a) (b)

Figure 6 Support element and system capacities for 100–150 mm thick fibre-reinforced shotcrete with embedded 8 mm mesh, resin bar (25 mm dia.), and cable bolts (15.2 mm dia.). (a) Load–displacement; (b) Energy–displacement

Using the peak work done by each support element and its respective activation timing and displacement capacity, a remnant support system capacity is calculated that represents the amount of energy capacity left in the system at a given displacement (Figure 7). As displacement occurs over time, capacity is consumed. The difference between installed capacity and consumed capacity is the remnant support system capacity. Therefore, a support system does not have an explicit capacity value that will be used for every design assessment because the SSC will vary based on the displacement demand on the support system.

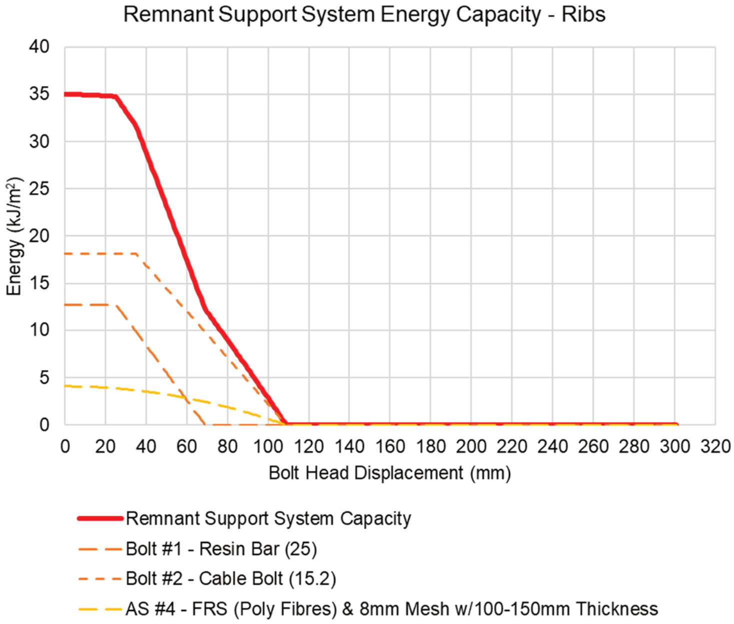


Figure 7 Remnant support element and system capacity for the support design described in Figure 6

Note that the resin bar and cable bolts are not activated, meaning they do not provide a load capacity, until 25 mm and 35 mm, respectively. Individual elements in a support system may be activated at different times, given by the variable d_i or displacement at installation (Kaiser & Moss 2021). This displacement at installation is a function of deformation in the excavation prior to support installation, the support installation timing, and the bolt seating.

3.1.3 Design acceptance

A table with FoS calculated for the load, displacement, and energy in the ribs conveys the FoS per loading stage (Figure 8). The green colours indicate the FoS meets the acceptance criteria, yellow denotes values where FoS is less than the acceptance criteria but greater than or equal to 1.0, and red highlights FoS values below 1.0.

In this example, the static load demand is far surpassed by the available support capacity and maintains an adequate FoS. However, the static load imposes continuous displacement demand on the support system, slowly consuming support capacity. By loading stage 10, the remnant SSC has been reduced to a level where it is overcome by the combination of additional static load and strainburst. The ground support design no longer meets the acceptance criteria by approximately June 2024. Note the displacement-based FoS remains above 1.0 at loading stage 10, based on the support system displacement capacity and the estimated static and dynamic displacements imposed on the system. However, due to continuous displacement consuming support capacity in the first 10 loading stages, the remaining energy capacity at the time of the strainburst is not enough to survive the demands of the burst and the resultant energy-based FoS is below 1.0.

SUMMARY OF DESIGN ASSESSMENT - ***Single Strainburst Event Survived?***

Stage	Frame	Date	Loading Condition	Factor of Safety - Ribs		
				Load	Displacement	Energy
				Static	Mid	Mid
0	085	Dec/2021	Pre-peak Loading	>3	1.7	2.3
1	086	Mar/2022	Pre-peak Loading	>3	1.6	2.2
2	087	Jun/2022	Pre-peak Loading	>3	1.6	2.2
3	088	Sep/2022	Pre-peak Loading	>3	1.6	2.2
4	089	Dec/2022	Pre-peak Loading	>3	1.6	2.1
5	090	Mar/2023	Pre-peak Loading	>3	1.6	2.0
6	091	Jun/2023	Pre-peak Loading	>3	1.5	1.9
7	092	Sep/2023	Pre-peak Loading	>3	1.5	1.8
8	093	Dec/2023	Pre-peak Loading	>3	1.4	1.5
9	094	Mar/2024	Pre-peak Loading	>3	1.3	1.3
10	095	Jun/2024	Pre-peak Loading	>3	1.1	0.7
11	096	Sep/2024	Pre-peak Loading	>3	0.9	0.0
12	097	Dec/2024	Pre-peak Loading	>3	0.5	0.0
13	098	Mar/2025	Pre-peak Loading	>3	0.4	0.0
14	099	Jun/2025	Pre-peak Loading	>3	0.4	0.0
15	100	Sep/2025	Peak Loading	>3	0.2	0.0
16	101	Dec/2025	Stress Shadow	>3	0.2	0.0
17	102	Mar/2026	Stress Shadow	>3	0.2	0.0
18	103	Jun/2026	Stress Shadow	>3	0.2	0.0
19	104	Sep/2026	Stress Shadow	>3	0.2	0.0
20	105	Dec/2026	Stress Shadow	>3	0.2	0.0

Figure 8 Acceptance criteria (FoS) table per mining stage for the back and ribs

The energy versus displacement graphs per stage visually show the remnant support capacity versus the demand per mining stage (Figure 9). The graphs illustrate that failure is expected at Stage 10 as described previously. The displacement demand is still less than the ultimate displacement capacity of the support system, though as highlighted numerically in Figure 8, it is below the required FoS. The energy demand at this displacement, however, exceeds the remnant capacity of the support system at 105 millimetres as shown by the demand line crossing above the red capacity line.

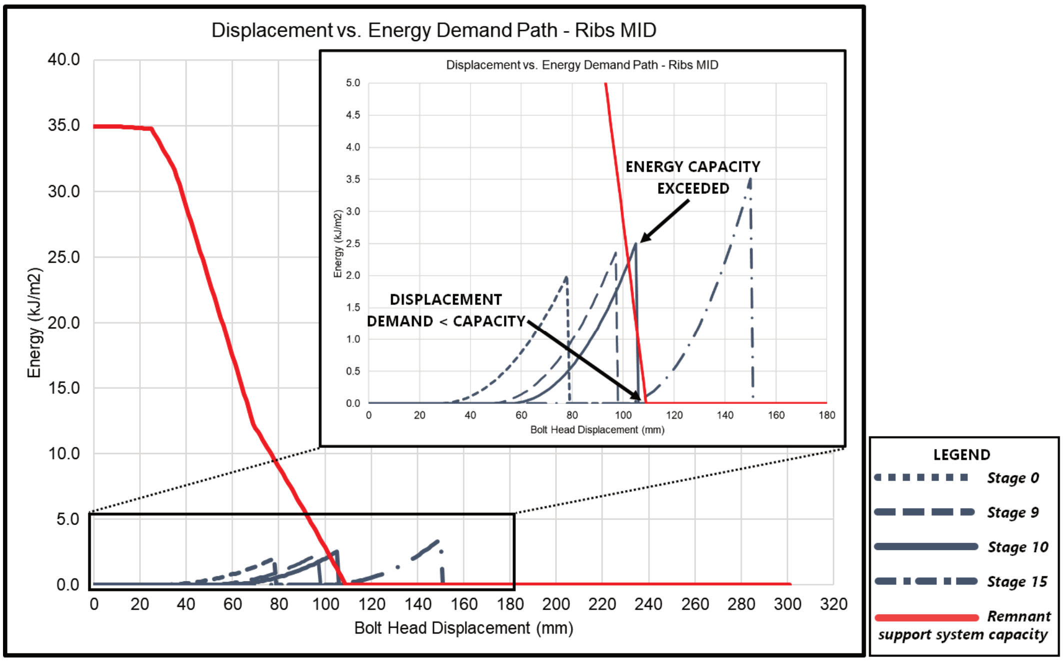


Figure 9 Displacement versus energy demand path for the mid-size strainburst event in the ribs

In this example, PSM must be installed to improve the support system capacity and its resiliency to future displacements and energy demand prior to the FoS falling below the stated acceptance criteria. The time from the current loading stage to the anticipated failure time represents the anticipated service life of the ground support. The service life of the support system aids in planning PSM by highlighting the expected stage of SSC exceedance. PSM timing is also communicated in terms of the cave extents or the distance from the excavation to the cave front to avoid potential confusion due to future deviations from the plan. Figure 10 shows the mine development and undercut extents at the calculated failure stage from the numerical model and highlights the excavation location. Ultimately, PSM or rehab is triggered by monitoring and not solely based on the calculated support design service life results.

Figure 10 Undercut caving outline and mine development at the calculated failure stage (Stage 10, June 2024)

4 Calibrated inputs

The demand and capacity calculations require calibrated inputs to produce reasonable estimations of support consumption and PSM timing. Using data collected at the DMLZ and GBC mines, site-specific inputs were determined for use in the design process.

4.1 Support element capacities

Individual support element capacities are direct inputs to the support system capacity calculations. Ground support element capacity has been assessed from site specific data where possible (e.g. pull-out tests (POT) and observations of ground support failure). Areal support elements were primarily determined from literature (Villaescusa et al. 2010).

4.2 Demand input parameters

Static and dynamic demand calculations rely on user-defined input parameters to accurately estimate the demand on a support system. Diederichs & Martin (2010) failure criteria for static depth of failure and displacement require two input parameters: spalling initiation threshold and static bulking factor. Both parameters were derived from borehole camera measurements combined with modelled stress estimates (spalling initiation threshold) or displacement data (bulking factor). Calibrated values exist for DMLZ, predominantly relying on PB1 data prior to 2018. GBC data informs the mine-specific values but is spatially limited considering the heterogeneity of the mine.

The dynamic demand calculations require three important inputs to calculate displacement and energy demand for the three different sized strainburst events. The strainburst depth of failure is assumed to be a ratio of the static depth of failure with certain minimum depths. The strainburst velocities are based on back analysed strainburst events at the GBC and DMLZ.

The empirical trends to estimate the depth of failure technically represent the condition with no support installed. However, the application of support provides confinement, suppresses spalling, and serves to reduce the depth of failure. By calibrating input parameters (e.g. bulking factor, spalling initiation threshold) based on measured data in the mining areas of interest, with the relevant ground support systems, the demand calculations provide the best possible estimates of realistic depths of failure.

5 Field verification

Verification work was undertaken to confirm the current design approach versus observations of ground support performance in the field. The validation exercise considered actual monitoring observations, PSM installation timing, and abutment position/loading.

The process included the following stages:

1. Selection of representative excavation segments

   Excavations were selected where notable bulking displacement was observed (at rib and/or back) and PSM or rehabilitation work has been completed. Ten locations in DMLZ were selected with five locations in both the undercut and extraction levels. The locations have either already experienced or are currently experiencing cave abutment loading.

2. GSST assessment

   The selected locations were then evaluated in the GSST using demand from the latest stress path, actual support components installed, and input parameters as provided in Table 1. Adjustment to some parameters (e.g. intact strength) were done within tolerable limits.

3. Design versus actual displacement comparison

   The displacement demand calculated from the GSST was compared against the actual monitoring observations, PSM installation timing, and abutment position/loading.

From this verification work, the following was concluded:

- The extent of displacement was reasonably replicated using the current DBSD approach.
- The abutment position/loading response was consistent with real observations.
- The timing of PSM/rehab was sufficiently simulated for long-term forecasting purposes.

Table 1 summarises the calculated displacement demand from the GSST versus actual displacement measured in the field prior to PSM/rehab. The 'simulated period of PSM' was the forecasted period when displacements exceed PSM thresholds. Meanwhile, the 'actual period of PSM' was the timing of measured displacement directly prior to PSM installation.

Measured displacements are presented for both convergence and scanning data. Differences between these specific displacement values are expected; convergence represents a single point, while scanning covers the entire drift. Both measurement methods are dependent on the timing of the baseline. The calculated versus actual PSM periods are also disrupted by changes to the undercutting schedule. In this example, the same undercut extents from the numerical modelling (Figure 10) might occur later due to undercutting delays.

These results highlight the complexity of single acceptance criteria to represent the entire life of the excavation. PSM was still required in these excavations despite the design process at the time considering the peak demand event at the maximum loading conditions. DBSD and PSM acknowledge these realities and provide estimates of when the support system is expected to be compromised to aid in operations planning and monitoring schedules. This approach provides an operationally viable method to manage workplace safety.

Table 1 Calculated displacement demand from GSSTv3.1 versus measured displacement from monitoring (before PSM/rehabilitation)

Site # and location	Calculated displacement demand (mm)	Calculated period when PSM is required	Measured displacement		Actual period of PSM
			Convergence (mm)	LiDAR scanning (mm)	
1 DD25E north	110	Jun – Sep 2020	125	50	Nov-21
2 DD24W north	106	Mar -Jun 2020	123	125	Feb-21
3 DD25W north	105	Sep – Dec 2020	132	75	Oct-21
4DD24W south	102	Dec 2020 – Mar 2021	187	50	Jan-21
5 DD24E south	116	Dec 2020 – Mar 2021	112	150	Jan-21
6 P26 DP06W-07W	105	Sep – Dec 2020	168	100	Nov-21
7 P27 DP07W-08W	107	Sep – Dec 2020	88	100	Nov-21
8 P23 DP09W-10W	104	Mar – Jun 2020	145	104	Mar-20
9 P24 DP14W-15W	94	Dec 2020 – Mar 2021	125	–	Aug-21
10 P22 DP13W-14W	96	Mar – Jun 2021	132	75	Apr-21

6 Challenges and next steps

The revised ground support design methodology requires regular feedback to accurately represent field conditions. Deformation monitoring is required throughout the excavations where PSM is anticipated to quantify the state of the support capacity and trigger PSM. Improved scanning technology for speed, frequency, and ease of processing will further aid in the application of PSM by increasing coverage. Input parameters for demand calculations must be assessed as the caves mature. Stress conditions will change and new rock mass conditions will be encountered. Routine updates of the stress path model are required to incorporate changes to undercutting sequence and draw schedule. Certain input parameters are difficult to calculate from empirical events, such as displacement at installation and strainburst bulking factor. Reviewing the validity of the current values against new demand events ensures the design inputs are appropriate.

At PTFI, scoping level ground support design takes place at the strategic design level, weeks or months ahead of excavation. Installed ground support design is performed by site-based geotechnical engineers with significant experience in the rock mass and stress condition being mined, as well as up-to-date access to ground conditions at or near the design location via recent heading inspection. Socialisation and training of the revised ground support methodology to both groups is a critical aspect of successful implementation. Design teams have been involved in the development of the revised methodology. Management has been routinely updated on the progress. Comprehensive documentation, including worked examples like the one in this paper, is being developed. In-person training in the updated tools will take place during the roll-out of the new method, as well as for new engineers. The next phase of work will focus on the following improvements to the design methodology and tools:

- Complete more capacity verification for individual elements and SSC.
- Consider calibrating the demand input criteria based on major geotechnical domains or typical stress conditions within each mine.
- Implement a transient bulking factor linked to proximity to undercut.
- Capture the bolt layout and its impact on the volume of rock failing between bolts (i.e. support resistance) in the capacity determination.

7 Conclusion

Transitioning PTFI's design practices to follow deformation-based support design has allowed the design to match the way that ground support is installed and managed in the field. It considers how individual elements work together in a support system to resist demand, beyond the peak displacement or load demand being imposed on the capacity of a single support element, as is evident in the field. It acknowledges the loss of capacity during the evolving loading conditions in a caving environment and highlights when additional support is required to improve the system's resistance to dynamic events. By reviewing the results of the new methodology against real PSM installations, this process shows a better match to observed deformations and better captures the reality of ground support performance. The use of PSM has been embraced by the operations and constitutes PTFI's method of excavation stability management both in planning and in practice.

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