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Dynamic support evaluations for implementation by seismic hazard domains

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Abstract

Dynamic ground support is a common component of risk management strategies in seismic mines. In this paper, dynamic ground support design is presented for a deep Canadian mine where dynamic support classes are established for seismic hazard categories based on potential rockbursting mechanism, the expected damage intensity, distance to design event, and design event magnitude. Considering support system survival limits and distance to probable design events, various aspects of support system functions are evaluated. Support system static capacity, deformation capacity, and energy capacity are analysed to evaluate support design strategy specific to probable events of a given magnitude occurring within a given distance. The final design includes multiple support system classes and guidelines on support class utilisation based on proximity to seismic hazard domains.

Keywords: *rockburst, seismic domains, dynamic support*

1 Introduction

Dynamic ground support is a tactical control for rockburst hazard management used in combination with other tactical controls (for example barricading and exclusion zonation) as well as various strategic (for example mine design and sequencing) controls. Dynamic ground support should be utilised in all mines with rockburst hazards (Stacey 2011). The utilisation of dynamic ground support, in conjunction with other engineering and administrative controls, provides means to improve workplace safety in underground mine plants where bursting conditions are encountered. Further, dynamic ground support systems provide significant value add to mining operations where reduced costs associated with rehabilitation and mitigated loss of process are achieved. Despite the significant value add when dynamic support systems are implemented appropriately, there are inherent risks to cost and productivity when dynamic support systems are implemented more extensively than necessary (as consumables and cycle-time costs increase with support system intensity; commonly exceeding those of static support systems). Therefore, the implementation of dynamic ground support systems should be optimised by design and utilisation of support classes applicable to seismic hazard domains which can be established by spatial and temporal zonation of seismic hazard categories. Demonstrating domained design for dynamic ground support is the objective of this paper.

2 Case study seismic domains

The case study investigated in this paper is a gold mine complex in Canada which currently operates at approximately 1,000 m below surface and is planned to extend to 1,500 m depth in future life of mine (Figure 1). The mining plan primarily uses a longitudinal longhole stoping with retreat typically towards central level accesses, thereby creating diminishing central access pillars. Active development and production are progressing in four mining horizons, with a bottom-up sequencing in each horizon. Sill pillars are established between each of the mining horizons and are recovered by uphole stoping leaving small rib and skin pillars in place. Additionally, barren pillars are created locally in the plane of the ore where unmineralised areas (such as dykes) or uneconomical regions exist. Some transverse stopes are planned in deeper sections of the mine where the orebody is wide with primary–secondary sequence. Dadashzadeh et al. (2023) provide case study information and a detailed discussion of seismic hazard domains for the site.

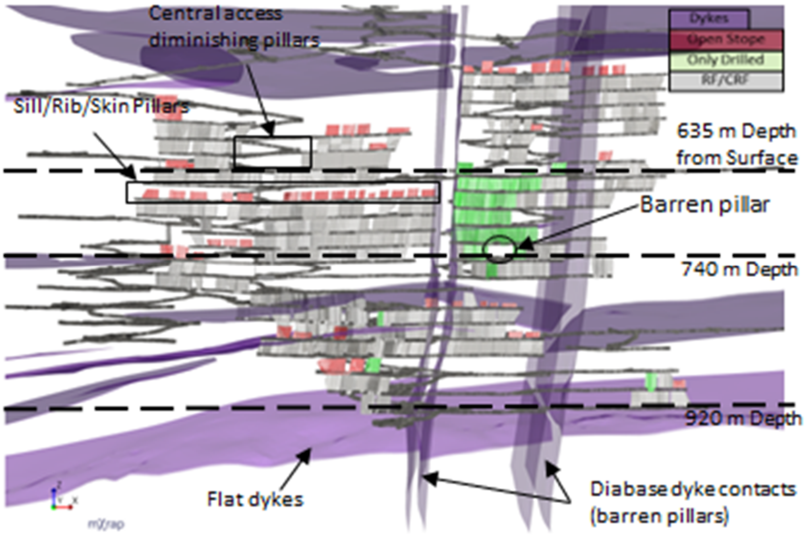

Figure 1 Long-section view of mine showing key pillar types and distribution of modelled dykes

The spatial delineation of the seismic domains relies on an understanding of site-specific influencing parameters which have been identified by analyses of unusual occurrence and mine-wide seismic data (i.e. pillars and geological structures, as noted earlier and described in Dadashzadeh et al. 2023), with refinement of spatial hazard at the local-scale according to proximity with conditions susceptible to the influencing parameters. When defining a seismic hazard domain, it is necessary to establish probable event magnitude, event location, damage mechanism, as well as likely displacement and energy demands imposed on a ground support system (Kaiser & Cai 2012). Spatial domains have been defined for the case study site according to rock mass volumes impacted by spatial influencing parameters (sill pillars, diminishing pillars and dykes), as well as by temporary (ore sills) and permanent (all footwall development) excavation classes for volumes not within the rock mass regions associated with influencing parameters. Table 1 provides a summary of seismic hazard domains that have been defined for this site, which are relied on to establish classes of dynamic support systems as demonstrated in this paper. These hazard domains are based only on event magnitude ranges; future work efforts are required to improve hazard domains with consideration for seismic source mechanism.

Table 1 Seismic hazard domains and associated design events.

Seismic hazard category	Seismic hazard domains	Design event (M_L)
Static	Development above 635 m depth	NA
Low	Footwall (FW) development above 860 m depth Abutment mining above 860 m depth	+1.0
Moderate	FW development below 860 m depth Abutment mining below 860 m depth Diminishing central pillars Barren stope pillars	+1.5
High	Sill pillars (top 2 levels) Exposure to dykes (flat/ore parallel/north–south diabase)	+2.6

3 Dynamic support design

The objective of dynamic support is to manage excavation damage associated with potential rockburst events. Ground support design for dynamic conditions requires identification of the expected bursting mechanism and estimation of the expected damage intensity (both factors are required to define the anticipated demand placed on a support system). It is noted that the evolution of seismic hazard at this site is relatively recent and so, while it is necessary to establish mitigating controls, the design of such controls remains data limited. Due to very few cases of excavation damage related to rock bursting at this site, key design parameters such as ejection velocity, and damage depth have not been observed and/or documented. It is noted that these parameters can be resolved by seismic source mechanisms, however, specific seismic events contributing to rockburst damage have not been identified for application to the source model as described by Kaiser & Malovichko (2022).

The following information is known:

- Seismic hazard domains have been established (Table 1) with maximum probable event magnitudes which can be relied on for design events. The largest probably seismic events are associated with pillars and structures, and these hazards are well-suited for design methods considering remote events (i.e. design for shakedown and energy transmitted by large seismic events).
- Except for exposure to dykes, hazard domains are spatially associated with abutments and pillars where stress concentrations are well understood (by numerical modelling conducted at the site, which is not the subject of this paper), and so design methods must also account for strainburst hazard (static and dynamic bulking as well as the energy emitted by a strainburst).

With consideration for the above stated knowns and unknowns, the support design methodology employed for this site is intended to establish initial ground support design relying on as-installed system capacities. System capacity consumption (see Kaiser & Moss 2021) – a critical component of support system maintenance – is not described in this paper and can be managed by support system maintenance. To establish the initial ground support design, five steps have been employed.

Step 1: identify the anticipated mechanism/s. Three rockburst mechanisms must be considered for support design, as described by Kaiser et al. (1996):

1. Violent ejection of rock blocks due to seismic energy transfer. Damage incurred during dynamically loaded rockbursting is magnified by, and related to, the magnitude of the triggering remote seismic event (Kaiser & Cai 2013). Support systems must have adequate energy absorption capacity to withstand the kinetic energy of the ejected rock which is a function of the magnitude of the seismic source and its distance from the opening.
2. Volumetric expansion (bulking). Where ejection does not occur with bulking, ground support systems must have sufficient strength capacity to suppress bulking or have sufficient elongation capacity to accommodate bulking related to the progressive fracturing process. When ejection occurs with bulking, the support system requires sufficient energy dissipation capacity in addition to adequate static and elongation capacity to withstand both bulking and transferred kinetic energy (remaining stored strain energy after energy consumption by fracturing) on the failing volume.
3. Seismically induced rockfall (shakedown). Support systems must be designed with added static factors of safety to stabilise the marginally stable rock volumes.

Step 2: identify the anticipated damage severity. Damage depth is a critical design input for dynamic ground support. In the absence of field measurements, guidelines from literature may be relied on to establish preliminary designs. However, where observational data are available these should be relied on over generalised published guidelines. For each bursting mechanism described in step 1, the damage caused may vary in severity and this is best predicted by knowing or estimating the mass of loose or fractured rock involved. Damage intensity can be broadly characterised as follows (Kaiser et al. 1996):

- Minor: rock spitting, spalling or shallow slabbing.
- Moderate: rock is heavily fractured and may have displaced violently.
- Major: impassable excavation due to substantial amounts of displaced rock.

It is noted that numerical methods provide alternative means to predict damage depths, however, reliance on numerical simulations requires good quality field data for back-analysis calibrations and substantial sensitivity testing to bound reasonable ranges of damage depth. In the absence of field data for model calibration, practitioners are cautioned against false confidence in numerically predicted damage depths as rockburst failure mechanisms are very complex and uncertain due to inherent rock mass heterogeneity. Further, damage depth estimations at the excavation scale require advanced mechanistic modelling approaches which are often computationally expensive and generally only prioritised for explicit event back analyses rather that generalised mine-wide studies. It is the authors' experience that damage depths bound by published empirical guidelines provide reasonable ranges comparable to both numerical predictions and field observations and are therefore suitable for initial support system design until confidence is gained by field observation and measurements.

Step 3: determine the required support system design characteristics (based on steps 1 and 2). An effective support system is comprised of individual support elements working together to achieve reinforcing, holding and retaining functions.

Step 4: identify the performance characteristics of support elements based on their specifications and support demand analyses (i.e. select design parameters). This study has considered three primary bolt types: rebar, Yield-Lok and Par1 (based on site-specific supplier and equipment constraints). Surface support elements considered include 6-gauge weld-wire mesh and 0-gauge strapping. Rockbolt element capacities utilised for this study are summarised in Table 2. For any support design implementation, support element capacities should be verified prior to extensive utilisation, and then routinely verified by quality control testing programs during the implementation (guidance on support system implementation is discussed later in this paper). Capacity parameters are not provided for mesh and strap elements. These elements are negated from the design capacity formulations based on two assumptions: (1) load is transferred to bolts via the anchored segments and (2) the surface support is sufficiently robust to retain broken rock until bolts fail. Surface support is discussed further in Section 3.2.

Step 5: match support element design characteristics with the required performance characteristics (support functions) to assemble an appropriate support system.

Table 2 Ground support specifications as provided by the suppliers

Support element type	Component	Value
Yield-Lok bolt (20 mm)	Tensile strength	178 kN
	Elongation	8%
	Energy absorption capacity	42.6 kJ
Par1 resin bolt (20 mm)	Tensile strength	224 kN
	Maximum elongation	22%
	Energy absorption capacity	54 kJ
Resin grouted rebar (20 mm)	Tensile strength**	150 kN
	Maximum elongation (10–13%$^+$)	11.5%
	Energy absorption capacity (1–4 KJ*)	2.5 kJ

*From Kaiser et al. (1996); **Site-specific static capacities; + ASTM International (2019)

3.1 Support demand assessments

Support demand evaluations have been conducted for drift spans of 5.0 and 6.5 m. Analyses consider varying design events according to the hazard domains defined by Dadashzadeh et al. (2023) and reasonable ground damage intensity and deformation estimates. Factor of Safety (FOS) results are presented for static, strain and energy demand components of primary support bolting patterns to demonstrate the evaluation methodologies appropriate for triggered strainburst potential as well as dynamic loading from near-field faults or structures (Kaiser & Cai 2012). In accordance with Kaiser & Cai (2012) and more recent work by Kaiser & Moss (2021), multiple rockburst damage mechanisms have been analysed separately in order to identify the critical support demands for each of the distinct hazard categories.

3.1.1 Static load demand

The static load demand aims to stabilise rockfalls (seismic shakedown). Rockfall can occur when a volume of rock, that is stable under static conditions, is accelerated by a remote seismic event. For this reason elevated static strength factors should be used in dynamic ground conditions. Figure 2 illustrates the static strength factors for support system survival limits based on event magnitude and distance from event as provided by Kaiser et al. (1996). According to these thresholds, the distance to an event for various FOS targets has been determined for each design event (as listed in Table 1). The minimum distance considered is 10 m distance as the failure mechanism for static support evaluations is rockfall induced by seismic shaking. Within 10 m, this study assumes that an event is considered near-field and the dominant failure mechanism expected would then be volumetric expansion or violent ejection.

Distance to Design Event

Design Event (ML)		**Target FOS**			
		9	**3**	**1.5**	**1.1**
Low	**1**	<10 m	<10 m	<10 m	11 m
Moderate	**1.5**	<10 m	<10 m	10 m	20 m
High	**2.6**	10 m	17 m	35 m	70 m

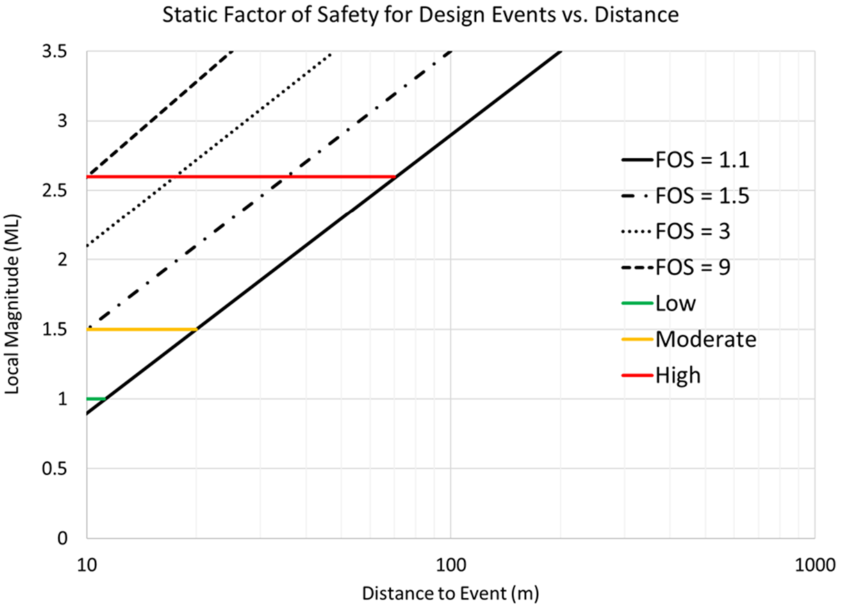

Figure 2 Survival limits as a function of static strength factor (as provided by Kaiser et al. 1996). Summary table lists the distance to event for various FOS targets

To evaluate static load design requirements, consideration must be given to wedge kinematics as well as the dead weight load of damaged rock mass around an excavation periphery. Design methods for wedge kinematics are widely published and understood in rock engineering and as such, these analyses are not demonstrated within this paper. To evaluate the potential dead weight load of the damaged rock mass volume, it is first necessary to determine the severity of damage or the mass of failed rock. For this case study, there is very limited damage depth data available to define this critical design input. Damage depth was observed and reported for a single site-specific unusual occurrence where drift back failure was reported to be 1–1.5 m. In the absence of more routine field measurements, damage depths have also been estimated by empirical guidelines from the literature. Kaiser et al. (1996) suggest that 0.75–1.5 m damage depth is appropriate for moderate to heavy damage in spans less than 5 m. This can be scaled linearly to 1–2 m damage depth for 6.5 m spans (which is in good agreement with the unusual occurrence damage noted above).

The maximum static load demand (Ls) to hold the dead weight load of failed rock can be formulated as follows:

$$Ls=\rho gAd \tag{1}$$

where:

ρ = density (2,740 kg/m^3).

g = gravity (9.81 m/s^2).

A = the surface area per bolt (m^2).

d = depth of the damage zone (m).

Resulting static FOS analyses for various bolt densities and types can be resolved by the tensile capacities of rockbolt elements and the anticipated dead weight loads (as shown in Figure 3) to determine appropriate bolting patterns to satisfy static load criteria for each seismic hazard domain according to the distance to event FOS targets summarised in Figure 2.

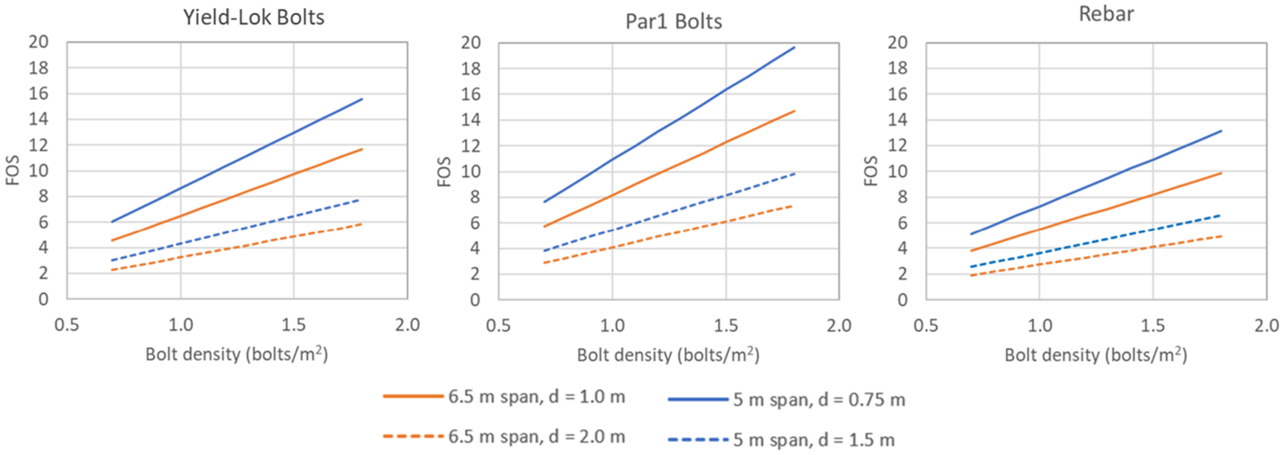

Figure 3 Static FOS results: comparing event distance, excavation span, bolt types and bolting densities

3.1.2 *Strain demand*

Dynamic support systems must be able to accommodate bulking deformations which may be imposed by both static and/or dynamic displacements. The strain demand can be established based on the expected volume increase due to bulking during the fracturing process. The bulking factor (BF) is defined as follows (Kaiser et al. 1996):

$$BF=\frac{u_w-u_{df}}{d_f} \tag{2}$$

where:

u_w = wall displacement.

u_{df} = displacement at the failure radius (or rockbolt anchor if bolts are shorter than failure radius).

d_f = depth of fracturing (or the bolt length).

The BF will vary for supported and unsupported conditions. In supported conditions, yielding elements may be required to survive rock mass bulking. Stiff and strong support in combination can help to minimise damage depths and the degree of bulking (Kaiser et al. 1996). Kaiser et al. (1996) guide that yielding support with an average capacity less than 200 kN/m^2 it is appropriate to assume a BF of 5±1%, and this range of bulking is consistent with magnitudes discussed in more recent publications, for example, Kaiser & Moss (2021). Conservatively assuming a BF of 6%, the FOS for strain demand in the Yield-Lok bolt is therefore 1.3 (8% elongation capacity/6% elongation demand), the Par1 bolt is 3.6 (22% elongation capacity/6% elongation demand), and the rebar bolt is 1.9 (11.5% elongation capacity/6% elongation demand). These FOS evaluations rely on the following assumptions:

- Unidirectional strain is perpendicular to the excavation boundary and parallel to the rockbolt axis. This assumption should not be relied on in ground conditions susceptible to strongly anisotropic failure. In strongly anisotropic conditions, support element selection must give critical consideration to bolt shear strain capacities.
- Bolt elongation is distributed along the length of the bolt (within the damaged zone). It is noted that in situ rebar bolts, in particular, compared to the Par 1 and Yield-Lok bolts also under consideration, are unlikely to achieve the elongation demand of a bulking rock mass due to the stiff performance of this bolt type; deformation in the rock mass would be expected to localise strain between the rebar ribs (i.e. locally overstraining relative to the 6% rock mass bulking). However, it is also noted that rebar will be more effective (than Par 1 and Yield-Lok) at reducing the BF. Thus, BF with rebar is conceptually reduced (even where local rebar failure occurs) and unfortunately this is difficult to quantify for design.

3.1.3 Energy dissipation demand

For situations where strainbursting or rock ejection by seismic energy transfer may occur, it is necessary to evaluate energy dissipation demand. Dynamic support designs are plagued by uncertainties pertaining to rock mass conditions (largely due to heterogeneity) and loading system stiffness; these uncertainties make it very difficult to achieve reliable estimations of ejection velocity by either analytical or numerical tools. Where crushing-type events are identified, the source model described by Kaiser & Malovichko (2022) provides means to resolve displacements and event duration (and hence an average ‘ejection’ velocity). Where specific strainburst events are not identified (as is the case for this study), scaling laws provide an industry standard guideline for estimating velocity contributions to energy formulations. These, of course, should be supplemented with site-specific field observations of ejection and displacement magnitudes when possible.

The rock’s ejection velocity during dynamically loaded rockbursting can be related to the magnitude of a seismic event and the distance from the seismic source to the opening by scaling laws provided by Kaiser et al. (1996).

$$v_{max} = \frac{C \cdot 10^{a(M_R+1.5)}}{R} \tag{3}$$

where:

M_R = seismic magnitude according to Richter scale (for this case study, local magnitude is in Richter scale).

C = constant set to 0.25 (mine specific seismic data should be used to calibrate this parameter).

a = constant set to 0.5 (mine specific seismic data should be used to calibrate this parameter).

R = distance to the seismic source (m).

This formulation by Kaiser et al. (1996) assumes that the mine opening is in far-field conditions (as defined by Kaiser & Maloney 1997). For near-field large magnitude events, it is reasonable to assume an upper bound of 3 m/s (Mikula 2012). Figure 4 illustrates the maximum velocity relative to distance from source as predicted by Equation 3 with a 3 m/s cap based on design event magnitudes ($M_L = M_R$) and distance to source (R).

To evaluate support design strategy specific to probable remote events of a given magnitude occurring within a given distance, energy capacity evaluations have been analysed as listed below:

- v_{max} = 3 m/s for excavations within 17 m of high hazard (M_L2.6) domains.
- v_{max} = 1.5 m/s for excavations:
  - Within 17–35 m of the boundary of high hazard (M_L2.6) domains.
  - Within 10 m of moderate hazard (M_L1.5) domains.
- v_{max} = 0.8 m/s for excavations:
  - Within low hazard (M_L1.0).
  - Beyond 10 m of the boundary of a moderate hazard (M_L1.5) domain.
  - Beyond 35 m of the boundary of a high hazard (M_L2.6) domain.

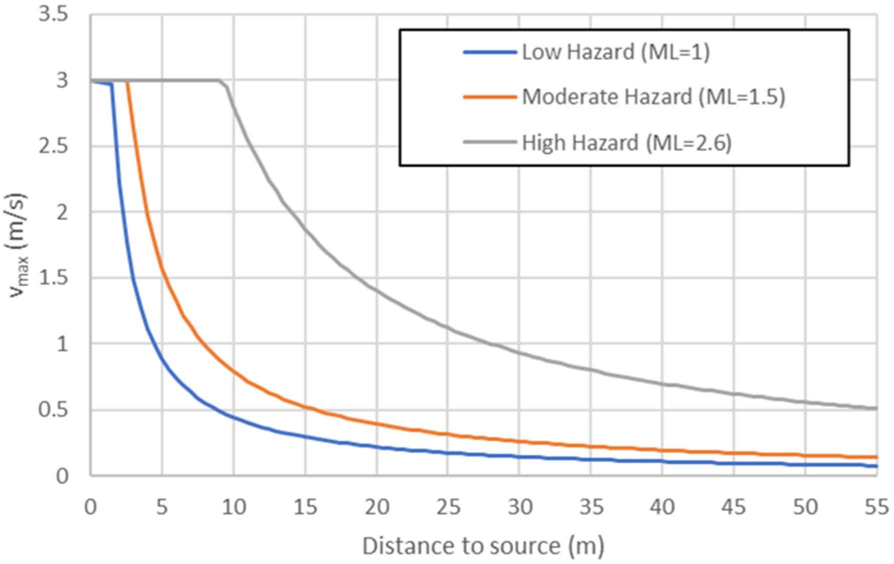

Figure 4 Change in ejection velocity based on event magnitude and distance to source

For the case study site, data is insufficient to resolve ejection velocities for strainburst events. Recall that due to very few cases of excavation damage related to rock bursting at this site, ejection distance and damage depths are not observed and/or documented. Further specific seismic events contributing to strainbursting have not been identified. The preliminary dynamic support designs achieved for this study assume that reasonable strainbursting ejection velocities are captured per hazard domain by the velocity magnitudes summarised above; explained as follows:

- $v_i = v_{max}$, where events are independent of distant seismic event ground motion and v_i is the velocity of the inner edge of the burst volume.
- $n{\cdot}PGV = v_{max}$, where a distant seismic event dynamically accelerates a strainburst volume (Kaiser et al. 1996) and n is a potential magnification factor and PGV is peak ground velocity).

It is acknowledged that assumptions pertaining to strainburst velocities introduced design uncertainty and these assumptions will require review as additional site-specific observations and data become available.

Once ejection velocity is established, the energy demand placed on a ground support system is defined as follows:

$$E = \frac{1}{2} m v_{max}^{2} + qmgd \tag{4}$$

where:

m = the mass of failed material (kg); with damage depth uncertainty acknowledged in this study this parameter considers burden volume + ½ burst volume for strainburst events.

q = 1 for backs and 0 for walls.

g = gravity (9.81 m/s^2).

d = displacement (m).

Figure 5 plots FOS results (resolved by rockbolt energy absorption capacity and energy demand as per Equation 4) at varying bolt densities and depths of yield (for 5–6.5 m spans) for low to high seismic hazard conditions. The data presented here respects the following assumed constraints as field observations of damage depth are very limited, and no site-specific data pertaining to displacements are available:

- Damage depths as follows:
  - Low hazard (M_L1.0): 0.75 and 1.0 m for 5 and 6.5 m spans, respectively.
  - Moderate hazard (M_L1.5): 0.75–1.5 m and 1.0–2.0 m for 5 and 6.5 m spans, respectively.
  - High hazard (M_L2.6): 1.5 and 2.0 m for 5 and 6.5 m spans, respectively.
- Displacement estimates can reasonably rely on two conservative empirical approaches (6% bulking deformations within the fractured volume for all hazard levels and 0.3 m, as follows:
  - Low hazard (M_L1.0): 6% bulking of fractured volume.
  - Moderate hazard (M_L1.5): 6% bulking of fractured volume to 0.3 m displacement.
  - High hazard (M_L2.6): 6% bulking of fractured volume to 0.3 m displacement.

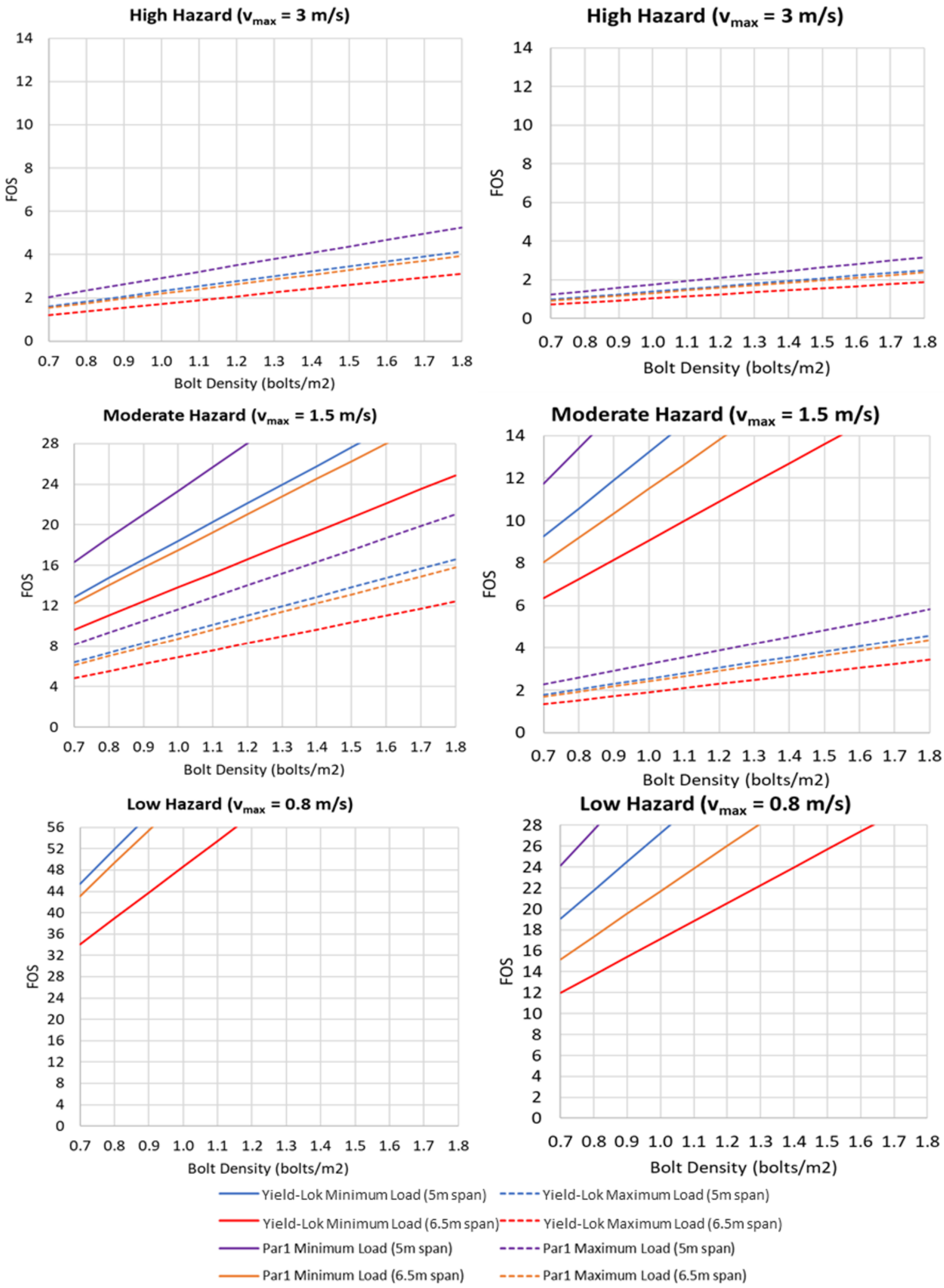

Figure 5 FOS for energy absorption in backs (right) and walls (left) under various seismic hazard conditions and varying bolt spacing. Minimum and maximum load refers to the moderate and heavy damage conditions

3.2 Surface system compatibility

The last component of dynamic support design is an assurance of system compatibility. Support elements must be combined as a system to satisfy support function and design criteria. According to the guidelines provided by Kaiser et al. (1996), the following surface support elements are considered in this study:

- Low hazard: 6-gauge welded-wire mesh in back and walls.
- Moderate hazard: 6-gauge welded-wire mesh with 0-gauge strapping in back only.
- High hazard: 6-gauge welded-wire mesh with 0-gauge strapping in back and walls.

3.3 Support design classes

Based on the static, strain and energy demand evaluations, seismic hazard intensity relative to distance from seismic source, as well as surface support function and performance, three classes of primary dynamic ground support are proposed to establish preliminary dynamic support designs for this case study (applicable for spans up to 6.5 m). The three support classes are itemised below with criteria summarised in Table 3. For each design event, ground support demand is dependent on the distance from the seismic source. Therefore, dynamic support classes have application zones as summarised in Table 4.

For bolt length design, moderate damage condition is considered for support class 1 (0.75–1 m depth of damage for excavation spans of 5 and 6.5 m respectively), while heavy damage condition is considered for support classes 2 and 3 (1–2 m damage for 5 and 6.5 m span respectively). Minimum bolt lengths by span are then defined to achieve at least 0.5 m anchorage beyond the assumed damage depths (assuming the effective bolt length is 0.15 m less than the total bolt length to account for the bolt head), while not being less than the bolt length defined in static support standards (which is required to satisfy kinematic wedge stabilisation).

3.3.1 Support class 1

- Backs: Yield-Lok or Par 1 on a 1.5 × 1.5 m square pattern with rebar bolts on dice (0.9 m bolts/m^2). Yield-Lok or Par 1 bolts must be installed on the screen overlaps. Note the rebar dice bolts are not strain compatible with the Yield-Lok or Par 1 bolts. The intention of the mixed pattern is to provide adequate energy capacity (Yield-Lok and Par 1) while minimising bulking (by stiff rebar elements).
- Walls: Rebar on a 1.5 × 1.5 m dice pattern (0.9 bolts/m^2).
- 6-gauge welded-wire mesh with minimum three square overlap installed to within 1.5 m of the floor.
- 1.8 m bolt for back spans ≤ 5 m and walls up to 6.5 m high.
- 2.4 m bolt for back spans 5–6.5 m.

3.3.2 Support class 2

- Backs*:* Yield-Lok or Par 1 on a 1.5 × 1.5 m dice pattern (0.9 bolts/m^2).
- Walls: Yield-Lok or Par 1 on a 1.5 × 1.5 m square pattern with rebar bolts on dice (0.9 bolts/m^2).
- 6-gauge welded-wire mesh with minimum three square overlap installed to within 1.5 m of the floor.
- 0-gauge strapping oriented lengthwise along the drifts (back only) at 1.5 m spacing.
- 2.4 m bolt for back spans and wall heights ≤5.5 m.
- 2.7 m bolt for back spans and wall heights 5.5–6.5 m.

3.3.3 Support class 3

- Backs and walls: Yield-Lok or Par 1 on a 1.2 × 1.2 m dice pattern (1.4 bolts/m^2).
- 6-gauge welded-wire mesh with minimum three square overlap installed to the floor (within 1.0 m).
- 0-gauge strapping oriented lengthwise along the drifts (back and walls) at 1.2 m spacing (lowest row of strapping within 1.0 m of floor).
- 2.4 m bolt for back spans and wall heights ≤ 5.5 m.
- 2.7 m bolt for back spans and wall heights 5.5–6.5 m.

Note: Bolt spacing adjustments between classes (1.5–1.2 m) may require sourcing of variably mesh screen size.

Table 3 Dynamic ground support class application zones

Support class	Seismic hazard	Design event (M_L)	Distance to design event	Target static FOS	Target energy absorption FOS	Design ppv	Design damage depth for 5 m span	Design displacements
1	Low	1	Within seismic domain	1.5	1.5	0.8 m/s	0.75 m	6% bulking of damage
	Moderate	1.5	>10 m					
	High	2.6	35–55 m					
2	Moderate	1.5	<10 m and within seismic domain	1.5–3	1.5	1.5 m/s	1.5	6% bulking of damage
	High	2.6	17–35 m					
3	High	2.6	<17 m and within seismic domain	3–9	1.5	3 m/s	1.5	0.3 m

Table 4 Seismic hazard domains and application zones of dynamic support classes

Seismic hazard category	Seismic hazard domains	Design event (M_L)	Distance to domain (m)	Dynamic support class
High	Sill pillars (top 2 levels), Exposure to dykes (flat/ore parallel/north–south diabase)	2.6	<17 and within seismic domain	3
			17–35	2
			35–55	1
Moderate	FW development below 860, abutment mining below 860 level, diminishing central pillars, barren stope pillars	1.5	<10 and within seismic domain	2
			>10	1
Low	FW development above 860 level, abutment mining above 860 level	1.0	Within seismic domain	1
Static	Development above 635	NA	Within seismic domain	NA

4 Implementation and ongoing review of dynamic support system design

The implementation of new or modified support systems should trigger change management procedures. For ground support systems, a change management process would include aspects such as:

- Formal risk assessment.
- Operator training for equipment and/or support element changes.
- Job observations and inspections.
- Material testing (including pull testing to verify bolt and anchor capacities). Design capacities may initially be based on supplier specification and published records (as is the case for this case study). The actual support element capacities must be verified by field testing and if the results vary significantly from those assumed in this analysis, the implications to design must be evaluated.

4.1 Resolving uncertainties

Ongoing data collection should aim to resolve design uncertainties identified in this study, enabling dynamic support design review and refinement. Common uncertainties during early design phases are summarised here, with suggested actions for mitigation.

- ***Damage depth*** is a critical design input for dynamic ground support and must be determined by field observations. It is highly recommended that sites collect this data for design verification in active mining areas and establish a damage depth data collection process geared towards routine data collection. Damage depth data collection processes may include:
    - Probe hole surveys using borehole cameras conducted in multiple locations for each design domain to achieve observation of damage depths.
    - Observed depth of damage recorded where support system failures occur.
    - Conventional instrumentation to monitor damage depths (and displacement magnitudes) such as borehole extensometers.
    - Numerical simulations where calibration data is available.
- ***Large event mechanism:*** Large magnitude events can occur as fault slip or pillar bursting mechanisms. Distinguishing between these two mechanisms is critical since each mechanism has implications for ground support design and the localisation of damage potential (see Dadashzadeh et al. 2023 for a case study discussion of large event mechanisms).

4.2 Experienced based design inputs

For all rockbursts and unusual occurrences, investigation and documentation should include classification of the mechanism type, quantitative observations of damage severity, and record of observed ground displacement magnitudes. Further, to quantify support effectiveness, sites should develop a site-specific ground support damage history chart including information on the distance to the seismic source. Recommended investigative details to be populated in an unusual occurrence database include event date/time, magnitude and source location, areas inspected (areas observed with no damage can also be populated in the database), and distance to the seismic source, as well as the type of ground support installed, location of ground support damage (back, shoulder, wall, wall below support and spatial coordinates) and severity and nature of ground support damage.

4.3 Instrumentation and monitoring

Monitoring programs should be established to target deformation. Deformation monitoring offers the opportunity to monitor for the consumption of ground support capacity (even where failure events have not occurred). The accumulation of relatively small (non-failure) deformation can progressively consume support system capacity, resulting in diminished residual capacity and potential for support system failure during dynamic loading (Kaiser & Malovichko 2022; Kaiser & Moss 2021). Periodic laser scanning surveys provide means to monitor support system conditions (this is particularly valuable in high risk/high exposure conditions where there is little tolerance for elevated excavation vulnerability). Conventional instrumentation, such as borehole extensometers, also provides valuable data pertaining to damage depths and bulking magnitudes.

4.4 Design reviews

Reviews of the ground support systems should be immediately triggered under the following circumstances:

- Observations of damage depth in excess of what has been assumed for design basis.
- Strainburst observations can be correlated to specific crushing-style events to allow for more rigorous assessment of bulking duration and burst damage depth.
- Magnitude of observed seismicity exceeds the magnitude of design events defined as design basis (or if predicted seismic potential changes during ongoing data reviews and analyses).
- Occurrence of any support system failures.

4.5 Development of seismic hazard maps

As site-specific experience is gained, a critical step for seismic hazard management and support utilisation is the development of seismic hazard (or rockburst hazard) maps. Effective hazard mapping requires spatial evaluation of seismic potential and excavation vulnerability.

4.5.1 Seismic potential

Seismic potential requires characterisation of rock mass and structural seismic response to mining, related to geology (lithology and distance to structure), stress (in situ and mining-induced) mine geometry, and operational practices.

Rockburst hazard mapping requires as-built and designed geometries with assigned attributes describing:

- Geology (lithology and distance to seismogenic structures).
- Stress (from numerical stress modelling, at time of excavation development and over operating life of excavation). Stress models should be routinely updated to verify stress model calibration as mining progresses and account for changes to mine plans.

4.5.2 Excavation vulnerability

Excavation vulnerability is influenced by numerous factors including void geometry, support system capacity, stress loading, geological factors and support system condition (Kaiser 2017; Kaiser & Cai 2013; Heal et al. 2006). Rockburst hazard mapping requires as-built and design geometries with assigned attributes such as span (design and as-built), installed ground support type or class, observations or measurements of support system quality/condition, monitoring of excavation condition (for example conventional instrumentation, laser scanning for deformations and/or damage mapping), and analyses of stress levels and their changes.

5 Conclusion

Dynamic ground support is a tactical control for rockburst hazard mitigation used in combination with other tactical controls (for example barricading and exclusion zonation) as well as various strategic (for example mine design and sequencing) controls. Efficient utilisation of dynamic ground support requires that support classes applicable to seismic hazard domains be established for the appropriate spatial and temporal implementation of support for specific hazard categories. Dynamic support domaining has been demonstrated. The engineered approach for the dynamic support design described in this paper incorporates site-based evidence, literature-based empirical relationships and analytical calculations to achieve an appropriate dynamic support design for site-specific expected conditions.

Ground support design is an iterative process, further, to demonstrating an effective design process, guidance is provided for implementation and ongoing review of support design. Common design uncertainties include damage depth and displacement magnitudes and strainburst ejection velocities. Resolving these uncertainties through routine observation and monitoring provides critical means to improve design confidence.

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