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Dynamic ground support design for burst-prone mines: a systematic framework integrating the burst envelope

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Abstract

Rockbursts are sudden, violent failures of rock around underground excavations and may result from strainbursts, pillar bursts or fault slip bursts. Despite extensive research, the need for a unified and reliable methodology for designing ground support systems under dynamic load, persists. This paper reviews existing dynamic ground support design methods and introduces an energy-based 'burst envelope' framework for preliminary assessment of rockburst potential. Defined in 3D principal stress space, the burst envelope links rock material properties, specimen size effects, and in situ stress conditions to evaluate the likelihood and severity of strainbursts. By considering different stress paths under true-triaxial loading–unloading conditions, the approach provides mechanistic insight into strainburst initiation, addressing limitations of conventional empirical indices.

The study further evaluates key methodologies, including the methods outlined in the Canadian Rockburst Handbook, the rockburst damage potential (RDP) and Western Australia School of Mines (WASM) approaches, as well as numerical modelling techniques for underground rockburst assessment and ground support design in dynamic loading conditions. Limitations are highlighted, particularly in estimating dynamic demand parameters such as peak particle velocity (PPV), which are affected by wave propagation and geological heterogeneity. Key ground support functionality requirements are discussed, emphasising the need for integrated system behaviour under dynamic conditions. A hybrid design framework is proposed, combining burst envelope-based assessment, empirical and analytical methods, and calibrated numerical modelling, continuously updated through field monitoring and back-analysis. This integrated approach provides a pathway toward a more consistent and mechanism-informed design methodology for dynamic ground support design in underground mining.

Keywords: *rockburst, strainburst, dynamic ground support, burst envelope*

1 Introduction

Rockbursting is the sudden and violent failure of rock around an underground excavation. Events are commonly classified as self-initiated or seismicity-induced and include the following mechanisms (Askaripour et al. 2022; Dunn 2017; Kaiser & Cai 2013, 2012; Kaiser et al. 1996; Kaiser & Moss 2022; Potvin & Hadjigeorgiou 2020; Verma 2020; Verma et al. 2024):

- strainburst
- pillar burst
- fault slip burst

Several methods have been developed to assess rockburst potential, but no single approach provides a reliable basis for designing ground support under dynamic loading (Potvin & Hadjigeorgiou 2020). Current practice combines empirical methods, analytical approaches, numerical modelling and site observations.

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These methods are generally applied separately and rely heavily on engineering judgement. The following sections review established and emerging approaches, and identify the requirements for an integrated dynamic ground support design framework.

2 Data collection and preliminary seismic hazard assessment

In current industry practice, rock characterisation is primarily based on laboratory testing of underground core samples, complemented by geological mapping and core logging. Laboratory testing provides the fundamental rock properties (Verma et al. 2018; Verma et al. 2019; Verma & Chandra 2020; Verma et al. 2021). These are often interpreted alongside field observations to estimate representative rock mass characteristics. These data commonly support rock mass classification, structural interpretation and stability analyses for static ground conditions. Such approaches are generally effective for evaluating static loading conditions dominated by gravity-driven, structurally controlled failure mechanisms and remain standard practice in the mining industry.

However, the same datasets can also be utilised to provide a preliminary assessment of dynamic failure mechanisms, including rockburst potential. Numerous empirical rockburst indices have been proposed based on combinations of rock strength and mechanical properties, such as uniaxial compressive strength, tensile strength, brittleness, elastic modulus, stiffness, and in situ stress conditions. While these indices are useful for preliminary assessment, most are derived from empirical curve fitting and provide limited insight into the underlying mechanisms governing burst initiation. Askaripour et al. (2022) provide a comprehensive review of these approaches.

The recently developed burst envelope concept addresses these limitations by establishing a mechanistic relationship between rock material properties, including strength, elastic characteristics, and fracture energy, specimen size effects, and the prevailing in situ stress state (Verma et al. 2024).

3 Ground support elements and system design philosophy

Ground support comprises rock reinforcement and surface support, which perform different but complementary functions. Reinforcement strengthens the fractured rock mass, limits bulking and anchors the damaged zone to competent ground. Surface support retains loosened rock between reinforcement elements, maintains confinement and transfers load through plates, straps and connections. Under dynamic loading, these components must act as an integrated system. Reinforcement elements work largely in parallel around the excavation, while surface support and its connections transfer load to the reinforcement in series. The capacity of the system is therefore governed by compatibility between load resistance, displacement capacity and energy absorption; not by the strongest component considered alone (Kaiser et al. 1996; Cai & Kaiser 2018).

Figure 1 relates the principal damage mechanisms in burst-prone ground to the reinforcement, retention and holding functions required from the support system (Kaiser & Cai 2012).

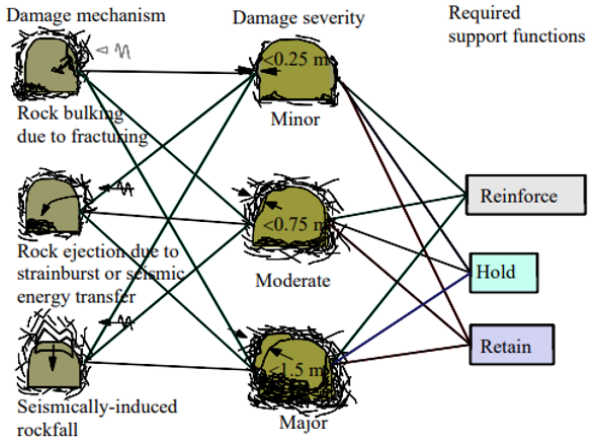


Figure 1 Rock damage mechanisms and corresponding ground support functions (after Kaiser & Cai 2012)

The required load path and interaction between reinforcement, surface support and connections are shown schematically in Figure 2.

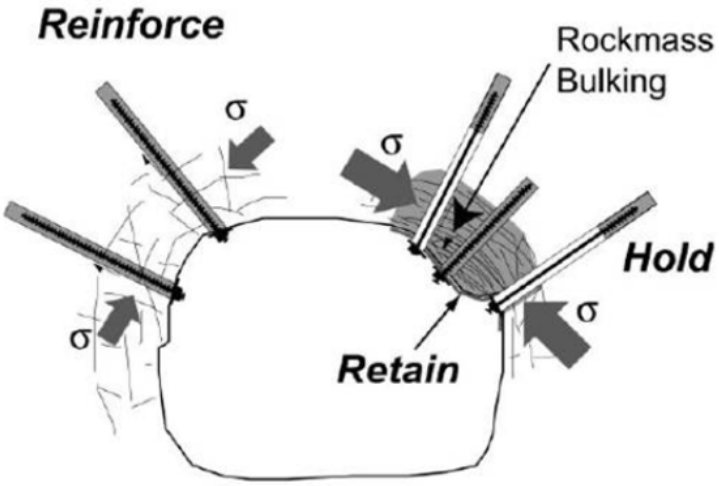


Figure 2 Functional interaction of reinforcement, surface support and connections within an integrated ground support system (after Kaiser et al. 1996; Kaiser & Cai 2012)

Table 1 summarises the principal surface support systems used in burst-prone excavations and their intended functions. The reported capacities were obtained under different test configurations and are not directly comparable. Most values are derived from laboratory testing and may not represent the performance of installed systems. Broader reviews, including full-scale test evidence, are provided by Cai & Kaiser (2018), Morkel et al. (2023) and Brändle & Roth (2024).

Table 1 Surface support elements (Cai & Kaiser 2018)

Name	Function	Total displacement capacity (mm)	Energy absorption capacity (kJ/m^2)
Weld mesh	Retain	250	<10
Chain link mesh	Retain	500	<12
Chain-link mesh (Tecco)	Retain	>300	50
Fibre-reinforced shotcrete	Retain	2–20	3–6
Mesh-reinforced shotcrete	Retain and dynamic load transfer	100–250	15–20
Strap/mesh strap	Enhance retaining function	120–200	42–55
Cable lacing	Retain	150 to 400	20 to 40

Cable reinforcement is used where the required anchorage length or supported volume exceeds the practical range of rockbolts. Table 2 distinguishes current cable configurations by load-transfer mechanism and intended dynamic role. Published capacities depend on strand construction, debonded length, grout quality, borehole geometry and test configuration. The values should therefore be obtained from project-specific qualification testing or current supplier data rather than transferred between systems.

Table 2 Cable bolts (Cai & Kaiser 2018)

Name	Function	Strength (MPa)	Displacement capacity (mm)	Energy absorption capacity (kJ/m²)
Cable Bolt	Reinforce and hold	1,860	20–40	3.1 (not debonded)
Dynamic cable bolt	Dynamic energy absorption and hold	1,860	up to 300 mm	30 kJ (at 300 mm displacement)
Duracable	Dynamic energy absorption	1,860	>220	>19.3 kJ

Dynamic bolts sustain load while accommodating displacement through controlled elongation, debonding, ploughing or sliding. Table 3 lists published load, displacement and absorbed energy for defined tests. Bolt energy is reported per element or tested segment. It is not an intrinsic area-normalised property. Conversion to kJ/m² requires the installed bolt density and is therefore project specific.

Table 3 Representative published and manufacturer-reported performance of dynamic bolts

System	Reported load (t)	Total displacement (mm)	Energy absorbed (kJ/element)	Energy capacity (kJ/m²)	Source and basis
MDX bolt	15.8–18.4 yield	120–143	25	Requires installed bolt density	In situ axial dynamic tests and product data (Roach et al. 2019; Sandvik n.d.)
D-Bolt, 22 mm	28.5 impact	140	39 for 0.9 m test section		Laboratory drop test (Li & Charette 2010)
PAR1 Resin, 20 mm	22.8 static	190	54		Typical manufacturer value for 2.4 m bolt (Epiroc 2022a)
PAR1 Resin, 22 mm	27.7 static	205	69		Typical manufacturer value for 2.4 m bolt (Epiroc 2022a)
PAR1 Pumpable, 20 mm	22.8 static	200	50		Typical manufacturer value for 2.4 m bolt (Epiroc 2022b)
Posimix Dynamic, 20 mm	18.9 yield	96	21		WASM test 176, 1.0 m debonded length (Sandvik 2024)
Posimix Dynamic, 20 mm	18.9 yield	171	42		WASM test 208, 1.0 m debonded length (Sandvik 2024)
MD bolt	15.8–18.4 yield	250	20		Published in situ test data (Roach et al. 2019)

Conventional and quasi-static bolts remain useful where rapid displacement demand is limited or where they provide immediate support as part of a layered system. Table 4 summarises common options. These products should not be assigned dynamic capacity without relevant testing because anchorage loss, plate failure, bond failure and shear loading can govern before the bar reaches its nominal tensile capacity.

Table 4 Conventional bolts

Element	Load (t)	Total displacement (mm)	Energy absorbed (kJ/element)	Source basis
Swellex Pm12–Pm24	12.2–24.5 breaking	Not reported	Not reported	Manufacturer minimum breaking load. Omega-bolt testing reported 6.2 kJ per 100 mm sliding per metre of embedment (Player et al. 2009).
Mechanical end-anchored bolt	Not reported	Not reported	Not reported	No single published capacity applies across bar diameter, free length, anchor type and plate configuration.
Resin-encapsulated rebar	Not reported	Not reported	1–22	WASM tests on 20 mm threaded bar. Results ranged from early thread failure to plastic deformation of debonded section (Player et al. 2009, 2013).
47 mm Split Set	18.4 yield	Not reported	Not reported	Manufacturer yield load. Dynamic testing reported 2.7 kJ per 100 mm sliding per metre of embedment, not total element capacity (Player et al. 2009; Split Set Mining Systems 2024).

The values in Tables 1 to 4 should be used for product comparison only and not as design capacities. Most values originate from laboratory drop, pull or panel tests, or from manufacturer test programs. Installed performance is affected by drilling accuracy, encapsulation, grout or resin quality, corrosion, plate seating, mesh overlap, loading direction, repeated seismic events and the condition of the surrounding rock. Field performance can therefore differ substantially from component tests.

Comparative load–displacement curves for conventional bolt types are provided by Lorig & Varona (2013). Li et al. (2014), Cai & Kaiser (2018) and Knox & Hadjigeorgiou (2024) provide more recent discussion of conventional and energy-absorbing bolt behaviour, test configuration and the limitations of transferring laboratory results to the field.

4 A summary of dynamic ground support design methods

At present, no generally accepted method provides a reliable basis for designing ground support systems subjected to dynamic loading. Existing approaches may be grouped into 3 broad categories:

- Empirical methods that are site-specific and rely on observed damage, seismic response, and recorded support performance to guide design selection.
- Analytical methods, including approaches outlined in the *Canadian Rockburst Handbook*, estimate demand and support capacity from simplified energy and momentum relationships.
- Numerical methods evaluate stress redistribution, yielding, energy release, and support interaction for the excavation geometry and interpreted rock mass conditions.

Each method provides useful information, but none should be used in isolation. A robust ground support design requires comparison between empirical performance, analytical estimates, numerical modelling and field observations.

4.1 Empirical approaches

Common empirical approaches to dynamic ground support design include:

- rockburst damage potential (RDP) and excavation vulnerability potential (EVP) (Heal 2010)
- WASM approach (Villaescusa et al. 2016)
- site-specific empirical charting
- passive monitoring and back-analysis.

Heal (2010) developed the RDP scale and EVP framework from 80 rockburst case-histories across 13 Australian and Canadian mines. The approach is empirical and should be applied within the range of conditions represented by its database. Its predictions remain sensitive to site-specific geology, seismic-source characteristics, excavation geometry and support installation quality. EVP is therefore best used as a preliminary assessment and comparison tool rather than as a standalone design criterion (Heal 2010).

The WASM dataset is derived from laboratory drop testing of individual reinforcement and surface support elements (Villaescusa et al. 2016). Figure 3 is fundamentally a laboratory bolt-performance graph showing measured energy absorption and deformation at failure. Although presented by the authors as a design graph, it does not represent the response of an installed ground support system under field loading.

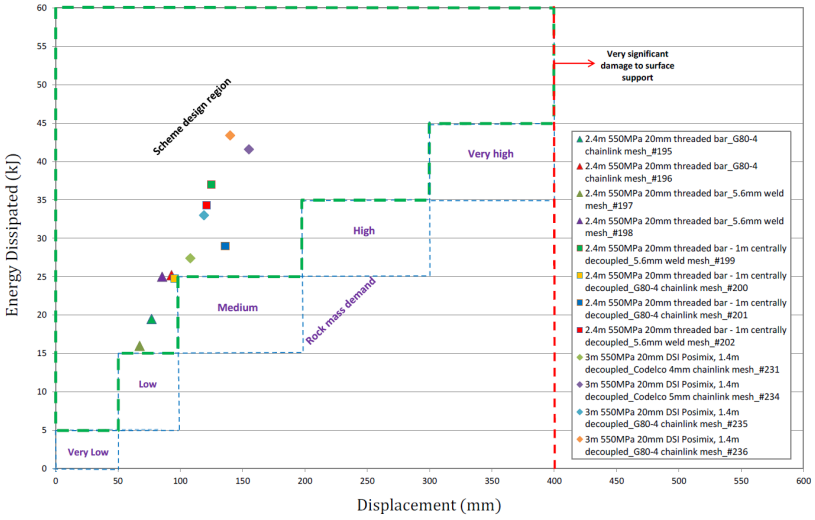


Figure 3 Laboratory-derived dynamic reinforcement performance graph, presented by Villaescusa et al. (2016) as a design graph

Site-specific empirical charting relates observed excavation damage to the local seismic hazard, ground conditions and installed support. Passive monitoring and event back-analysis allow these relationships to be updated as the mine develops (Morissette & Hadjigeorgiou 2019; Moss & Kaiser 2022; Graham et al. 2023). These methods are most reliable when the underlying database represents the conditions being assessed, and their application beyond that range should be treated with caution.

4.2 Analytical approaches

The *Canadian Rockburst Support Handbook* remains widely used for preliminary support selection in burst-prone ground (Kaiser et al. 1996). Its energy-based method compares the kinetic demand imposed by an ejected rock mass with the energy absorption capacity of the complete support system. The assessment requires estimates of the failed rock mass, ejection velocity and the proportion of demand transferred to reinforcement and surface support. These inputs are uncertain and should be constrained by site observations.

Deformation-based design treats mining-induced convergence as the principal demand for brittle, stress-driven damage (Kaiser & Cai 2013; Kaiser & Moss 2022). The anticipated depth of failure and bulking

of fractured rock are used to estimate wall displacement. This demand is compared with the deformation capacity and serviceability limits of the integrated support system. The method is most applicable to strainbursting where damage develops through stress fracturing around the excavation.

Dynamic support design requires separate checks of load and energy capacity. The load check confirms that the reinforcement, surface support and connections can retain the fractured rock mass. The energy check confirms that the system can accommodate the expected displacement or ejection without losing containment. Both checks should be applied to the complete support system because its response is often governed by the weakest connection or least deformable component.

Peak particle velocity (PPV) may be used to characterise ground motion, but it should not be treated as a direct predictor of damage extent. Damage also depends on the local stress state, excavation geometry, rock mass response, seismic-source mechanism and installed support. Where ground motion is required for demand assessment, Wesseloo (2018) provides a more appropriate near-source formulation that includes source radius and limits predicted amplitudes. The earlier inverse-distance expression in the Canadian handbook does not saturate near the source and can substantially overestimate PPV.

Analytical methods provide clear checks of support demand, capacity and deformation, but necessarily simplify failure geometry, loading history and interaction between support components. Their application should reflect the governing mechanism, whether strainbursting, seismic triggering or direct rock ejection, and should be calibrated against observed damage and installed support performance.

4.3 Numerical approaches

Numerical modelling extends the analysis where simplified analytical methods cannot adequately represent stress redistribution, progressive brittle failure, seismic-source behaviour or ground support interaction. Theselected formulation should reflect the expected failure mechanism, the scale of the problem and the field data available for calibration. The principal approaches are:

- Continuum methods, including finite element, finite difference and boundary element methods, represent the rock mass as a continuous material. They are suited to stress redistribution, yielding, excavation interaction and support loading where discontinuities can be represented implicitly or as discrete interfaces.
- Discontinuum methods, including discrete element and discontinuous deformation analysis, represent blocks and discontinuities explicitly. They are appropriate where joint slip, block rotation, structural release or fault movement governs the response.
- Hybrid methods couple continuum and discontinuum formulations. They permit fracture initiation and propagation within an initially continuous medium and are useful where brittle damage evolves into block release or fault-controlled movement.

Static/quasistatic numerical modelling analyses establish the pre-event stress state and identify areas susceptible to brittle failure. Dynamic analyses can then simulate rapid fracturing, structural slip, wave propagation and the resulting support demand. Seismic-source models provide a complementary means of assessing fault slip potential and the distribution of radiated energy. Advances in computational capacity have increased the use of these methods in rockburst assessment (Wang et al. 2021).

Model selection should be governed by the expected failure mechanism and the required design output. Input parameters should be constrained by laboratory testing and field measurements, while model response should be calibrated against observed deformation, seismicity and documented damage. Sensitivity analysis is required to establish the influence of uncertain inputs before the results are used for design.

5 The burst envelope

The burst envelope is a size-dependent, energy-based criterion developed to assess strainburst potential under polyaxial loading and excavation-induced unloading (Verma et al. 2024). It defines a surface in 3D

principal stress space that separates stress states capable of stable energy dissipation from states with sufficient excess energy for violent failure. The method links strength, elastic stiffness, mode-specific fracture energy, specimen dimensions and the expected localisation pattern. These quantities govern the energy stored before failure and the energy consumed as fractures initiate, propagate and coalesce.

A conventional yield surface identifies the onset of irreversible deformation. It does not establish whether failure will remain stable or accelerate into a burst. The burst envelope addresses this distinction through an energy balance. Stable fracturing is expected where the available strain energy can be dissipated by fracture growth and inelastic deformation. Bursting becomes possible where unloading releases more energy (rapidly in unstable form) than it can consume during the stable specimen cracking process. A scalar burst index describes the excess energy and provides a relative measure of burst severity.

5.1 Conceptual basis

The framework is intended for strain bursting in competent rock where excavation creates a rapid reduction in confinement.

5.2 Required inputs

Application of the method requires a reliable set of intact-rock properties. Strength and elastic stiffness define the stress state and recoverable strain energy before failure. Fracture energy defines the work required to create the localised failure zone. Specimen dimensions and the assumed localisation geometry control the conversion from material-scale fracture properties to the energy dissipated by a finite rock volume. These inputs should be derived from samples representative of the rock type and fabric under consideration.

Intact-rock properties should not be assembled from unrelated datasets without checking sample orientation, moisture condition, loading rate and scale. Anisotropic or foliated rock requires directional testing because strength, stiffness and fracture energy may vary with loading orientation. The stress path is equally important, and the initial principal stresses as well as the unloading direction should be aligned with the excavation geometry and mining sequence rather than a generic triaxial test path.

5.3 Envelope construction and interpretation

The burst envelope is constructed by comparing the recoverable strain energy associated with a stress state against the energy required to form the expected localised fracture zone. The calculation is repeated through principal stress space to define the boundary between stable and potentially violent response. No single principal stress or strength ratio controls the result. The position and shape of the burst envelope reflect the combined influence of confinement, stress anisotropy, elastic energy storage and fracture resistance.

Confinement increases the elastic energy that can be stored before unloading, raises rock strength and changes the mode of fracture. The resulting burst potential depends on the stress path rather than the initial stress state alone. The scalar burst index is therefore evaluated for the unloading path of interest. Values below the burst envelope indicate that the available energy can be dissipated. Crossing the envelope indicates that excess energy is available for kinetic release, with larger departures corresponding to a more severe response.

Two-dimensional sections through the 3D envelope provide a practical means of showing how confinement and stress anisotropy modify the transition from stable fracturing to bursting. A suitable presentation is proposed in Figure 4.

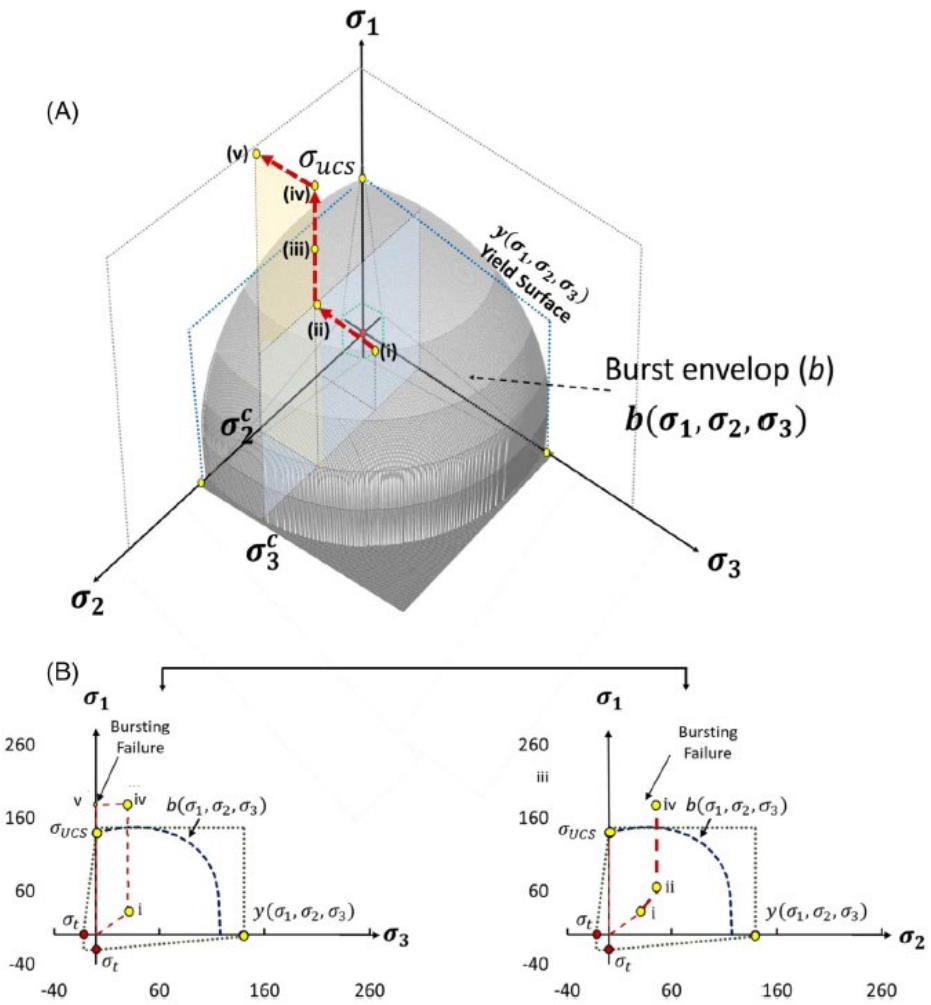


Figure 4 (a) stress path in 3D stress space with yield surface and burst envelope; (b) stress path in 2D stress space with yield surface (Verma et al. 2024)

5.4 True-triaxial loading and unloading paths

Verma et al. (2024) evaluated the framework using virtual true-triaxial strain-burst experiments. The stress paths reproduce the change in the in-situ stress state around the underground opening post an advancing excavation. This representation is more relevant than a conventional compression test because strainbursting is initiated by a change in boundary conditions. The model must therefore reproduce both pre-excavation energy storage and the unloading stage that releases this energy.

The published work (Verma et al. 2024) illustrates the functioning the developed burst envelope using 5 example stress-paths (SP1–SP5), as shown in Figure 5 below. SP1 crosses both the yield surface and burst envelope. Localised fracture develops and the released strain energy exceeds the dissipation capacity, this sudden release of excess stored strain energy produces strain bursting. SP2 stores substantial elastic energy but eventually remains inside the yield surface, so unloading produces elastic recovery. SP3 remains within both envelopes and is stable. SP4 represents high hydrostatic confinement resulting in significant increase in stored strain energy; however, can't release this energy due to the lack of unloading face (or continuity of hydrostatic stress state). SP5 crosses the yield surface but not the burst envelope and therefore produces stable inelastic deformation.

The 5 paths and their predicted responses should be shown together so that yielding, elastic unloading and bursting can be compared directly. Refer to Figure 5.

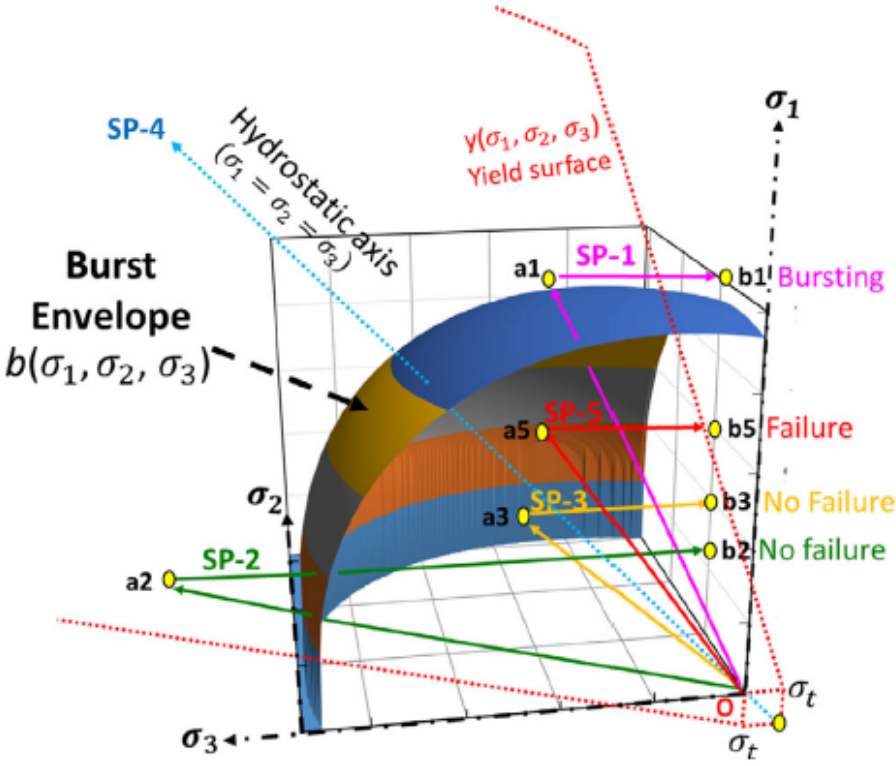


Figure 5 Energy-based strainburst envelope (Verma et al. 2024)

5.5 Mine-scale application

Mine-scale application should begin with domain-based laboratory testing and an estimate of the pre-mining principal stresses. Numerical stress analysis is then used to extract the loading and unloading paths around the proposed mining sequence. These paths are compared with the yield surface and burst envelope for each rock type. The resulting burst index can be mapped around excavations to identify locations where the stress path, material response and scale assumptions combine to produce elevated strainburst potential.

The mapped result should support, rather than replace, ground support design. It can indicate where deformation and energy capacity require closer examination, where mining sequencing may reduce rapid unloading, and where monitoring should be concentrated. The assessment should be updated as stress measurements, seismic response, observed damage and support performance become available.

5.6 Further requirements

The current formulation is based on intact-rock behaviour and idealised localisation. Rock mass structure, stress heterogeneity, excavation damage and discontinuity-controlled release are not represented directly. Fracture energy is difficult to determine and may vary with loading mode. The stress path obtained from numerical modelling is also sensitive to the assumed in situ stress field, constitutive model and excavation sequence. These uncertainties should be propagated through the assessment rather than concealed by a single deterministic burst index.

The burst envelope is therefore best used as a mechanism-based assessment and comparison tool. Its principal value is the consistent separation of yielding from bursting under a defined unloading path. Design decisions should combine this result with structural assessment, calibrated numerical modelling, seismic information, observed damage and the measured performance of installed ground support.

6 An integrated approach to dynamic ground support design

No single method provides a complete basis for dynamic ground support design. Empirical methods depend on the quality and relevance of available case-histories, analytical methods simplify the rock mass loading, damage and support demand generated by a burst event, and numerical models remain sensitive to constitutive assumptions and calibration. A robust ground support design should therefore use a combination of methods within an auditable process. The required outcome is not a single factor of safety, but a support standard with sufficient load, displacement and energy capacity for the credible failure mechanisms, together with defined controls for installation, exposure and review.

Dynamic support demand varies depending on the burst mechanism. For example, strainbursts develop through stress-driven fracturing, bulking and convergence close to the excavation while pillar and fault slip bursts involve larger unstable volumes and different patterns of load transfer. Events that originate away from the excavation can also shake down rock through the combined effects of ground motion and the exposed rock volume. These mechanisms should be assessed separately because each places different demands on the support system.

Ground motion is relevant where a seismic event contributes to the support demand. Its likely range depends on the event magnitude, the distance and direction from the source, and attenuation between the source and excavation. Mine openings, lithologies and major structures can modify the motion locally. PPV provides a measure of shaking intensity, but it does not predict damage by itself. Damage can be attributed to the local stress regime, excavation geometry, rock mass condition and the installed support system (Dunn 2017; Potvin & Hadjigeorgiou 2020).

6.1 The process

This section outlines a process for developing and maintaining dynamic ground support standards. The process begins by dividing the mine into design domains with similar ground conditions and seismic hazard. Each domain is characterised by:

- rock type
- structure
- stress
- excavation geometry
- mining sequence
- expected failure mechanism
- personnel exposure
- installed support

The supporting dataset includes laboratory properties, structural mapping, stress measurements, seismic-source parameters, damage records, rehabilitation history and support performance. Records from both damaged and undamaged excavations are needed to avoid bias toward poor performance.

Where sufficient site history is available, local relationships can be developed between event characteristics, source distance, excavation condition, support standard and damage severity. The installed condition at the time of each event is important, including bolt spacing, surface support continuity, rehabilitation, corrosion and known defects. Published charts provide useful context, but their direct application is limited where local conditions fall outside the source database.

Additionally, often mining sites conducts regular laboratory experiments to obtain and update their Geotechnical database. The use-case of such collected laboratory/field data are often limited to QAQC assessment. Instead, it’s applications and uses should be extended to the preliminary burst potential

assessment, which in collaboration with other approaches can help in developing robust dynamic underground assessment framework. This framework further requires re-calibration with time based on updating field/laboratory data set.

At mines with limited operating history, the initial design domains and support standards will contain greater uncertainty and should be conservative. Monitoring and back-analysis provide the basis for progressive refinement. Early designs should represent a credible range of demand rather than a single deterministic case, with sensitivity analysis used to focus further investigation on the assumptions that most influence the outcome.

Numerical modelling provides the link between the mining sequence and the likely spatial distribution of dynamic demand. Mine-scale models can define the evolution of stress and confinement, while local models may be needed where structural interaction or support response governs the outcome. Their value depends on calibration against observed deformation, damage and seismic response. Modelling can extend the site interpretation beyond mapped areas, but it cannot compensate for unreliable field data.

Support selection follows from the demand established for each design domain. Reinforcement must extend beyond the damaged zone and accommodate the expected movement without losing load capacity. Surface support must retain the fractured rock and transfer load to the reinforcement as deformation develops. Plates, straps, mesh, shotcrete and their connections therefore need compatible strength and displacement capacity. System performance is governed by the weakest part of this load path.

The design basis should state the expected failure scenario and the response required from the support system. These requirements are translated into a ground support standard suited to the hazard and operational exposure within each domain. Boundaries between support zones should reflect changes in ground behaviour and should avoid abrupt reductions in system capacity.

The installed capacity of the system depends on installation quality. Poor drilling, incomplete encapsulation or ineffective surface connections can prevent the specified support from developing its intended response. Verification should therefore concentrate on the installation features most likely to control performance, with the inspection effort matched to the consequence of failure. Defects should remain traceable until rehabilitation is complete.

The adequacy of the support standard is tested through observed performance. Reviews following significant seismic activity, deformation or support damage should establish whether the predicted mechanism and demand were realised and whether the support responded as intended. Mapping and instrumentation are most useful when they identify where the load path was lost, since this evidence distinguishes a design shortfall from an installation or maintenance issue.

Recalibration is required when field evidence changes the interpreted mechanism, demand or available support capacity. Review at key mining stages allows these changes to be incorporated before exposure increases, while unexpected damage or declining support performance may require an immediate response. In this way, the support standard develops with the mine rather than remaining fixed to the assumptions of the initial design. Figure 6 summarises the process from domain definition and support design to field verification and continuing review.

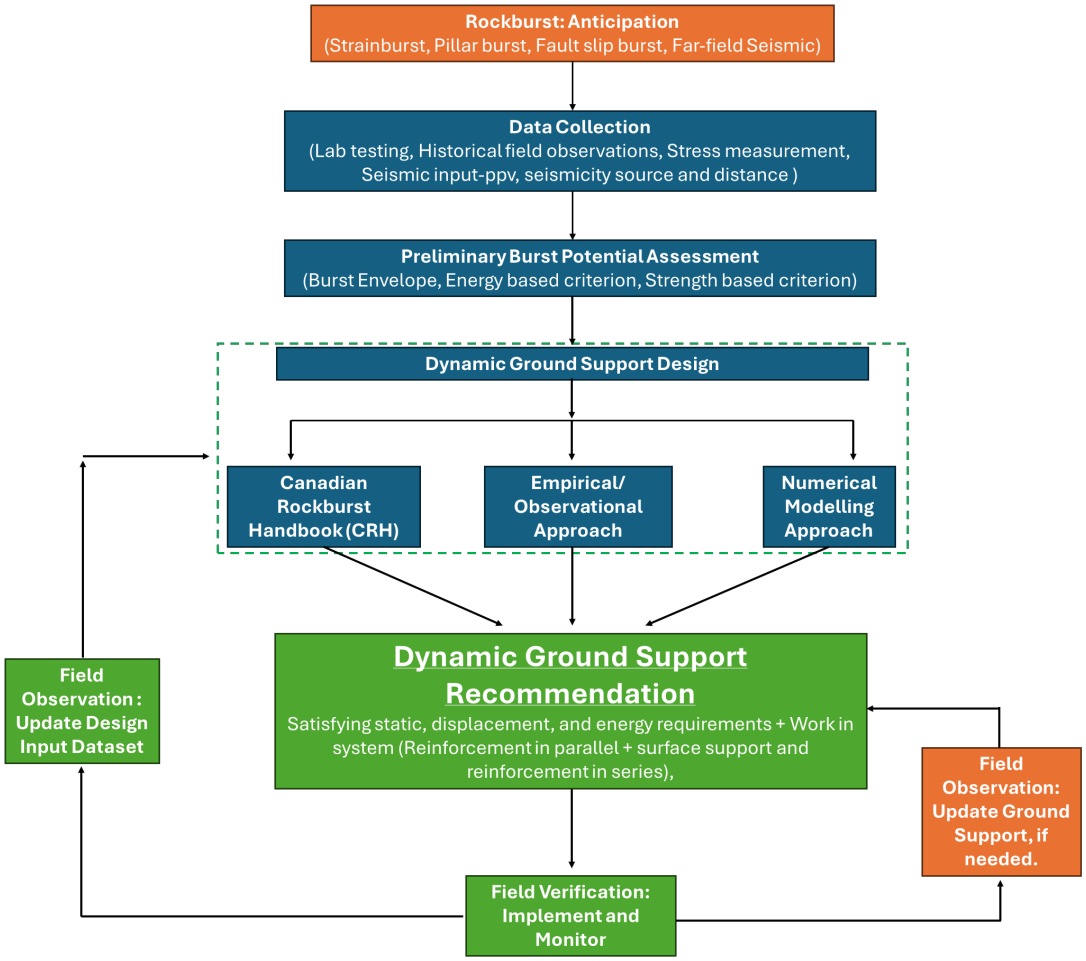


Figure 6 Systematic framework with burst envelope integration for dynamic ground support design

7 Conclusions

Dynamic ground support design remains challenging because no single method can adequately capture the range of rockburst mechanisms, dynamic demand conditions, and the response of installed support systems. This paper reviews the key empirical, analytical, and numerical approaches to dynamic ground support assessment and integrates them with the analytical burst envelope framework. The proposed methodology combines mechanism-based assessment (i.e., including energy-based burst envelope framework), site-specific geological and geotechnical evidence, calibrated numerical modelling, and observed support performance to develop and progressively refine ground support standards for burst-prone excavations. Particular emphasis is placed on understanding the relationship between the expected rockburst demand and the capacity and deformation characteristics of the in-situ ground support system, recognising that both demand and capacity are subject to uncertainty. These uncertainties should be explicitly considered throughout the assessment. Where practicable, sensitivity analyses and probabilistic approaches can help evaluate the influence of uncertain inputs on the predicted burst potential and support performance. The methodology should therefore be viewed as an integrated, iterative framework rather than a prescriptive design procedure, with assessments updated as new site data, monitoring results, seismic observations, and evidence of support performance become available. Ultimately, combining complementary assessment methods and systematic observational feedback provides a more robust basis for selecting, validating, and optimising dynamic ground support systems.

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