

# Bridging Element and System Scales: A Scale-Based Critical Review of Numerical Modelling for Dynamic Ground Support in Deep Hard-Rock Mines

Ashutosh Pratap Shastri

Ashutosh.jrf.min26@itbhu.ac.in

Indian Institute of Technology Varanasi

---

## Systematic Review

**Keywords:** Ground support, Rockburst, Dynamic loading, Numerical modelling, Deep hard-rock mining, Support–rock interaction, Microseismic calibration

**Posted Date:** July 22nd, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10431576/v1>

**License:**   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

**Additional Declarations:** The authors declare no competing interests.

---

# Abstract

As underground hard-rock mines extend to greater depths, elevated in-situ stresses and mining-induced seismicity increasingly subject ground support systems to dynamic, rockburst-type loading for which conventional static design approaches are inadequate. This paper presents a critical review of numerical modelling studies on dynamic ground support in deep hard-rock environments. A corpus of **92 studies**, identified through citation-network exploration and cross-validated against Scopus and Web of Science, was synthesized according to **physical scale** rather than topic: rock-mass-scale dynamic demand (22 studies), element-scale support capacity (37), system-scale phenomenological testing (18), and methodologically transferable research (15). Classification by **support–rock interaction capability** reveals a fundamental gap: although dynamic demand characterization, element-scale constitutive modelling, and large-scale field testing have each advanced considerably, **no reviewed study models the rock mass and support system as a fully coupled, dynamically interacting system**. The review argues that this limitation arises not from a lack of component-scale knowledge, but from the absence of an integrated modelling framework. A **physics-informed, microseismic-calibrated conceptual framework** is proposed to bridge rock-mass demand and support response, providing a roadmap for future mechanism-based, site-adapted design of ground support systems in deep, seismically active mines.

## 1. Introduction

As global mineral demand pushes underground mines to ever greater depths, the rock mass hosting these excavations is subjected to progressively higher in-situ stresses. In hard-rock environments, this depth-driven stress escalation is frequently accompanied by an elevated frequency and magnitude of mining-induced seismicity, ranging from minor stress-relief events to damaging rockbursts capable of ejecting rock at velocities sufficient to compromise both infrastructure and personnel safety. Unlike quasi-static rock mass failure, rockburst loading delivers energy to the surrounding excavation boundary over millisecond timescales, subjecting ground support systems to strain rates and kinetic energy demands that differ fundamentally from the conditions under which conventional static support design methods were developed.

This shift from static to dynamic demand has exposed a critical limitation in current ground support engineering practice. Empirically derived, static-capacity-based design approaches — while well validated for gravity-driven and stress-redistribution loading — do not reliably predict support performance when energy absorption, deformation capacity, and time-dependent material response govern the failure mode. Where dynamic testing has been introduced, it has largely proceeded along two separate and rarely intersecting research trajectories. The first characterizes the propagation of blast- and seismic-induced energy through the rock mass itself, typically treating any installed support as either absent or as a passive, non-interacting boundary condition. The second investigates the dynamic mechanical response of individual support components — rock bolts, mesh, and shotcrete — usually in isolation, under laboratory or explicit finite-element conditions that idealize the surrounding rock as a simplified, non-degrading medium. Site-scale field campaigns that test complete support systems under realistic dynamic loading do exist, most notably the large-scale simulated rockburst tests conducted over the past decade at LKAB's Kiirunavaara mine in northern Sweden and at the Walenstadt testing facility in Switzerland, but these remain phenomenological in character: they document observed system behaviour under specific site conditions rather than establishing a generalized, mechanism-based framework capable of predicting performance elsewhere.

The consequence is a body of literature that is individually sophisticated but collectively fragmented. Advances in explicit dynamic finite-element and discrete-element modelling now allow the yielding, rupture, and energy-

dissipation behaviour of individual bolts or mesh panels to be simulated with considerable fidelity; parallel advances in computational rock mechanics allow stress-wave transmission and destress-blasting effectiveness to be modelled with similar sophistication. Yet no numerical framework currently exists that couples these two scales – rock mass and support system – as a single, dynamically interacting structural unit, calibrated against real seismic demand from an operating mine.

This gap is particularly acute as mines such as LKAB's Kiirunavaara operation continue extending toward greater depths, where elevated in-situ stress and induced seismicity are expected to intensify. Reliable, mechanism-based prediction of ground support performance under these conditions – rather than reliance on generalized empirical capacity envelopes – is increasingly a prerequisite for safe and cost-effective mine design.

This paper critically reviews the numerical modelling literature addressing ground support performance under dynamic loading in deep hard-rock environments. Rather than organizing the reviewed literature by author, publication year, or narrow sub-topic, this review adopts a physical-scale framework, examining the literature sequentially at the rock-mass scale, the element scale, the site/system scale, and through methodological approaches transferable from adjacent high-stress excavation research. This structure is deliberately chosen to expose where current modelling capability is concentrated and – more importantly – where it is absent. The objective is threefold: (i) to critically synthesize the state of the art in dynamic numerical modelling of ground support across these scales; (ii) to identify the specific methodological barriers preventing an integrated, system-level modelling framework from emerging; and (iii) to propose a mechanism-based, site-calibrated modelling architecture capable of bridging this gap, using microseismic-informed dynamic boundary conditions as the basis for coupling rock mass and support response.

## 2. Literature Identification and Review Methodology

This review adopts a critical review methodology to synthesize current advances in the numerical modelling of dynamic ground support systems for deep, rockburst-prone hard-rock mining. The review was designed to provide broad coverage of the field while critically evaluating existing modelling approaches, identifying methodological limitations, and highlighting future research directions.

### 2.1 Literature Identification Strategy

The literature corpus was identified through citation-network exploration, seeded from foundational studies on dynamic ground support and rockburst mechanics and expanded through iterative forward and backward citation snowballing. This approach was selected to capture both seminal contributions and recent developments that keyword-based searches may overlook in long-established research lineages, such as the Kiirunavaara testing programme. To evaluate the coverage and representativeness of the resulting corpus, it was cross-validated against keyword-based searches in Scopus and Web of Science using combinations of terms related to mining environment, dynamic loading, ground support systems, and numerical modelling (e.g., FEM, FDM, DEM, Abaqus, ANSYS, LS-DYNA). Representative Scopus searches returned substantially larger result sets (e.g., 555 records), reflecting the broader literature on underground support and excavation engineering. The present review deliberately restricts its scope to studies addressing **dynamic loading and numerical modelling of ground support in deep, hard-rock, rockburst-prone environments**.

### 2.2 Inclusion and Exclusion Criteria

**Inclusion Criteria:** Studies were included if they: **(i)** were peer-reviewed journal articles or high-impact conference proceedings; **(ii)** focused on deep hard-rock mining environments or high-stress underground excavations with clear methodological relevance to dynamic ground support; **(iii)** investigated rock mass or ground support performance under dynamic or impact loading; and **(iv)** employed numerical modelling (e.g., FEM, DEM, FDM, or explicit dynamic analysis) and/or documented large-scale dynamic laboratory or field testing. A methodological exception was made for studies on deep high-stress caverns where microseismic monitoring, thermo-hydro-mechanical (THM) modelling, or excavation-induced loading methodologies were directly transferable to dynamic ground support analysis.

**Exclusion Criteria:** Studies were excluded if they: **(i)** addressed out-of-scope applications (e.g., shallow civil tunnelling or surface slope stability) without methodological transferability; **(ii)** relied exclusively on static analytical approaches without dynamic numerical or experimental validation; or **(iii)** did not evaluate ground support systems or rock mass response under dynamic loading, unless they contributed directly to the characterization of seismic demand. Institutional access was used to retrieve paywalled articles to minimize potential open-access selection bias.

## 2.3 Bibliographic Verification

Because citation-network exploration does not, by itself, guarantee bibliographic accuracy, every study in the final corpus was checked against primary bibliographic sources. This verification was conducted in two stages: first, direct comparison against a Scopus-exported bibliography with resolved DOIs; second, individual DOI resolution for records not captured in that export. Of the 92 studies comprising the final corpus, 79 (86%) were independently confirmed in this way — correcting, in the process, twelve instances where the author list, publication year, or exact title had been recorded incorrectly during initial identification. The remaining 13 studies (14%) were retained from the original citation-network identification without independent bibliographic re-verification; readers seeking to build directly on this review are encouraged to confirm these entries independently before relying on them.

The final corpus of 92 studies was subsequently categorized by physical scale of analysis — Rock-Mass-Scale Demand (22), Element-Scale Mechanics (37), System-Scale Phenomenological Testing (18), and Methodological Transfer / Data-THM Calibration (15) — rather than by topic, author, or chronology, in order to expose the scale-based structure of the coupling gap identified in Section 4.

## 3. State-of-the-Art Synthesis

Before presenting the scale-by-scale synthesis, Table 1 and Fig. 3 summarize two cross-cutting characteristics of the reviewed dataset: the methodological approaches used across all 92 studies, and their approximate geographic research origin. Both provide useful context for interpreting the scale-based synthesis that follows.

Table 1

Methodological approaches represented across the 92 included studies.

Each study is classified by its primary computational or empirical method; studies combining multiple methods (e.g., field testing with FEM back-analysis) are classified by their principal computational technique.

| Methodological Approach                | Number of Studies (of 92) |
|----------------------------------------|---------------------------|
| Finite Element Method (FEM/FE)         | 31                        |
| Laboratory Testing                     | 18                        |
| Field / In-Situ Testing                | 13                        |
| Literature Review (non-numerical)      | 11                        |
| Analytical Methods                     | 6                         |
| Conceptual / Design Philosophy         | 6                         |
| Microseismic / Data-Driven Methods     | 2                         |
| Physical Model Testing                 | 2                         |
| Discrete Element Method (DEM)          | 1                         |
| Peridynamic Simulation                 | 1                         |
| Conference Proceedings (non-technical) | 1                         |

### 3.1 Rock-Mass-Scale Demand: Wave Propagation, Rockburst Mechanisms, and Destress Blasting

The largest and most mature body of literature within the reviewed dataset focuses on the generation, propagation, and attenuation of dynamic loading within the rock mass, independent of installed support systems. These studies characterize the **demand** imposed on underground excavations—namely the magnitude, frequency content, duration, and spatial distribution of dynamic loading—but almost entirely neglect explicit support–rock interaction.

#### Rockburst mechanisms and classification.

Foundational classification frameworks proposed by He et al. (2012) and Cai (2013), together with later reviews (Wu et al., 2022; He et al., 2022; Waqar et al., 2023), establish the principal mechanisms governing rockburst occurrence, prediction, and mitigation. More recent investigations have refined understanding of specific triggering processes, including fault-controlled stress interactions (Yuan et al., 2025), dynamic buckling mechanisms in tunnel rockbursts (Deng et al., 2025), and blasting-induced failure in deep rock masses (Ding et al., 2026). Collectively, these studies substantially improve characterization of dynamic demand but model only the rock mass response, without explicitly representing installed reinforcement or surface support.

#### Stress-wave propagation and transmission.

A second research cluster examines stress-wave propagation through intact, fractured, and jointed rock masses. Numerical and theoretical studies have investigated wave transmission across discontinuities (Chai et al., 2017, 2020), impedance-controlled reflection phenomena (Wang et al., 2022), blast-hole delay interactions (Saadatmand Hashemi and Katsabanis, 2020), and dynamic fragmentation during rock cutting (Lu et al., 2017). Although these

works provide increasingly sophisticated descriptions of dynamic wave behaviour, support elements are absent from their numerical formulations.

#### **Destress blasting and seismic mitigation.**

Another major sub-theme addresses preconditioning techniques designed to reduce seismic demand before wave energy reaches excavation boundaries. Recent numerical and field investigations have evaluated the influence of residual rock mass properties on destress blasting (Zou et al., 2025), advance stress-release boreholes (Xie et al., 2024), field-scale blasting effectiveness (Fuławka et al., 2022; Yu et al., 2021), and geodynamic response to large-scale blasting (Eremenko et al., 2024). These studies demonstrate effective demand-reduction strategies but evaluate performance solely in terms of rock mass stress redistribution and seismic response, without considering the subsequent behaviour of installed support systems.

#### **Squeezing ground and tunnel closure.**

A smaller subset of studies (Hanumanthappa and Maji, 2017; Mombilia et al., 2025), together with the conceptual framework of Schubert (2004), investigates squeezing deformation and tunnel closure in highly stressed ground. Although squeezing represents a distinct loading mechanism from rockbursts, these studies are included because of their methodological relevance to deep underground excavation behaviour and support design.

#### **Synthesis.**

Across all **22** studies in this category, the Support–Rock Interaction Capability classification (Table 2) indicates that **20 studies contain no explicit support representation**, while the remaining **two** (Cai, 2013; Cai, 2024) consider support only conceptually or through uncoupled analytical approaches. Consequently, this literature provides a sophisticated understanding of **dynamic demand** but almost no representation of **support response**, establishing the first component of the support–rock coupling gap identified in this review.

### **3.2 Element-Scale Mechanics: Dynamic Behaviour of Bolts, Mesh, and Surface Support**

In contrast to the rock-mass-scale studies reviewed in Section 3.1, the largest body of literature in this review (37 studies) focuses on the **capacity** of individual ground support components to resist dynamic loading. This research area combines high-rate laboratory experimentation with increasingly sophisticated numerical modelling to characterize the behaviour of reinforcement elements under static, quasi-static, and impact loading. Despite its methodological maturity, the literature overwhelmingly evaluates support components in isolation, with the surrounding rock mass either neglected or represented as simplified, non-degrading boundary conditions.

#### **Energy-absorbing bolts.**

Research on dynamic rock reinforcement has progressively shifted from conventional high-strength bolts towards **energy-absorbing systems capable of sustaining large deformations while maintaining load-bearing capacity**. Laboratory investigations employing modified Split-Hopkinson tension bars, drop-weight impact testing, and controlled dynamic loading have established that controlled yielding, deformation capacity, and energy dissipation are the primary parameters governing reinforcement performance under rockburst loading (He et al., 2014, 2017; Hao et al., 2018; Chen et al., 2018; Pytlik et al., 2016). Complementary numerical studies have extended these findings through explicit finite-element modelling of reinforcement systems such as Conebolts and Superbolts,

while more recent investigations have examined constant-resistance large-deformation (CRLD) bolts, NPR reinforcement concepts, shear-dominated failure mechanisms, and remote-triggered strainburst conditions (Nguyen et al., 2018, 2019; Tao et al., 2016; Wu et al., 2019; Khaleghparast et al., 2023; Kabwe, 2023). Collectively, these studies have substantially advanced the understanding of reinforcement mechanics under dynamic loading, yet performance assessment remains largely confined to bolt-level behaviour without explicitly accounting for interaction with a deforming rock mass.

### **Welded wire mesh and surface support.**

Surface support research has predominantly investigated how installation configuration influences the mechanical response of welded wire mesh and flexible containment systems. Laboratory studies demonstrate that bolt spacing, bolt density, loading configuration, and testing methodology significantly influence mesh stiffness, deformation capacity, and energy absorption (Baek, 2018; Baek et al., 2020; Karampinos et al., 2018; Karampinos & Hadjigeorgiou, 2021, 2022). These findings are supported by field observations and quasi-static investigations (Whiting, 2017; Sengani, 2021; Kang et al., 2021), while recent impact-based studies have expanded the literature to include drop-mass loading and flexible protection systems under combined static and dynamic conditions (Batan et al., 2025; Tang et al., 2024; Yang et al., 2024). Broader reviews of reinforcement modelling and support requirements further confirm that this component-based testing paradigm extends across both hard-rock and coal mining environments (Vallejos et al., 2019; Wei et al., 2022). Nevertheless, the interaction between surface support and an evolving, dynamically fracturing rock mass remains largely unexplored.

### **Shotcrete and sprayed liners.**

Compared with bolts and mesh, comparatively few studies investigate the dynamic behaviour of shotcrete and thin spray-on liner (TSL) systems. Existing work combines high strain-rate laboratory testing with explicit finite-element analysis to characterize the material response of liner-supported rock specimens under dynamic compression (Wang et al., 2023). However, these investigations remain focused on material-scale behaviour rather than evaluating the performance of shotcrete or TSL systems within complete excavation-support assemblies.

### **Numerical methodology and constitutive development.**

Nozeres et al. (2021) compared implicit and explicit finite-element strategies for simulating quasi-static-to-dynamic fracture in ductile steel components, while Nielsen and Niordson (2019) developed a finite-strain gradient-plasticity formulation applicable to rate-dependent yielding. Karampinos et al. (2018) demonstrated discrete-element modelling of laboratory mesh testing, one of the few DEM treatments in this cluster.

### **Field-scale reinforcement practice and design strategy.**

A smaller group of studies documents reinforcement practice at the scale of a full excavation or roadway network, bridging the element-scale testing literature above with the larger excavation geometries more typical of Section 3.3. Kang et al. (2021) report a combined ground support-rock modification-destressing strategy specifically for 1000-metre-deep roadways under extreme squeezing conditions, integrating multiple reinforcement measures rather than a single component. Liu et al. (2024) document excavation response and reinforcement practice for large underground caverns at the Shuangjiangkou hydropower station, and Yang, F. et al. (2025) report surrounding rock deformation characteristics and corresponding control strategies for excavation through an abandoned roadway group. Potvin (2017) situates this practical reinforcement literature within a broader argument for new engineering-design technology in ground support, articulating the motivation for improved design tools that this

review's proposed framework (Section 5) is intended to help address. Although each of these studies engages with a full excavation or roadway geometry rather than an isolated laboratory specimen, the rock mass is still represented as a static or field-observed boundary condition rather than a dynamically interacting medium, consistent with the element-scale pattern identified below.

### **Conceptual and design-philosophy contributions.**

Several foundational, largely pre-2015 works (Kaiser and Cai, 2012; Potvin and Hadjigeorgiou, 2008a, 2008b; Stacey, 2011) establish the conceptual design philosophy underpinning much of the subsequent element-scale testing literature — articulating why energy absorption and deformation capacity, rather than peak static strength alone, should govern support selection in burst-prone ground.

### **Synthesis.**

The Support-Rock Interaction Capability classification for this cluster shows 33 of 37 papers classified as “Isolated Component,” with a further three classified as “Static Boundary.” Only Roth et al. (2014), drawing on instrumented full-scale field tests, achieves a “Phenomenological” classification. This pattern mirrors, from the opposite direction, the finding of Section 3.1: element-scale capacity is now modelled with considerable sophistication, but almost never in dynamic interaction with a representation of the rock mass actually delivering the load.

## **3.3 System-Scale Phenomenological Testing: Large-Scale Field Trials at Kiirunavaara and Walenstadt**

This section reviews the literature that comes closest to bridging demand and capacity: large-scale, in-situ dynamic tests of complete, installed ground support systems. This cluster of 18 papers is dominated by a single, decade-spanning research programme centred on LKAB's Kiirunavaara mine, supplemented by comparable work from the Walenstadt testing facility in Switzerland and earlier Australian field campaigns.

### **Origins.**

The methodological lineage of large-scale simulated rockburst testing traces to Heal and Potvin's (2007) foundational in-situ dynamic testing programme, which established the basic paradigm of using confined blasting to generate a controlled, quantifiable dynamic pulse against an instrumented support system. Potvin and Wesseloo (2013) and Stacey (2012) contributed complementary conceptual treatments of what constitutes an adequate dynamic demand test.

### **The Kiirunavaara test series.**

Beginning with Shirzadegan's (2014) development of an in-situ dynamic testing methodology, a sustained research programme — principally involving Shirzadegan, Nordlund, Zhang, Yi, Warema, and collaborators — has conducted and progressively reanalyzed a series of large-scale simulated rockburst experiments at the mine. Zhang et al. (2013) and Yi et al. (2016) established early numerical back-analysis techniques; Shirzadegan, Nordlund, and Zhang (2016a, 2016b) documented the large-scale test programme itself; Saiang and Nordlund (2016) extended this to explicit numerical simulation of large ground deformation; Shirzadegan and Nordlund's (2018) analysis and Yi et al.'s (2020) LS-DYNA-based simulation represent the most numerically mature treatments, followed by Shirzadegan, Warema, and colleagues' (2025) improved-design reanalysis and Warema's (2026) most recent evaluation.

This sustained, iterative reanalysis of substantially the same underlying field dataset — refined over more than a decade — is methodologically significant. It demonstrates that a single, well-instrumented field test series can support many years of productive numerical reinterpretation. It also reveals a structural limitation: because each successive study numerically reconstructs the same specific test geometry, blast configuration, and rock mass condition, the resulting models are calibrated and validated against one site-specific dataset rather than derived from a generalizable, mechanism-based constitutive framework applicable to other geological settings or support configurations.

#### **Complementary system-scale testing programmes.**

Outside the Kiirunavaara lineage, Vallejos et al. (2024) report dynamic test response data for complete ground support systems at the Walenstadt testing facility, providing an independent, methodologically comparable dataset. Masoudi and Sharifzadeh (2018) propose a reinforcement-selection framework based on matching ground demand to support capacity, and Stacey's (2016) treatment synthesizes system-scale observations into broader design guidance.

#### **Seismic hazard characterization at Kiirunavaara.**

Nordström, Dineva, and Nordlund (2020) perform a statistical back-analysis of short-term seismic hazard indicators preceding larger seismic events at Kiirunavaara, drawing on the same mine-wide instrumentation underlying the large-scale test programme, and offering a natural candidate input for the microseismic-calibration approach proposed in Section 5. Most recently, Gebremedhin et al. (2026) introduce higher-order dynamic parameters and time-dependent metrics for characterizing in-situ ground support test results.

#### **Synthesis.**

The Support-Rock Interaction Capability classification for this cluster is markedly different from the two preceding sections: 11 of 18 papers achieve a “Phenomenological” classification, reflecting genuine, empirically observed rock-support interaction under real dynamic loading — the highest interaction fidelity available anywhere in the reviewed literature. A further four papers are classified as “Empirical (No FEM),” and three as “Conceptual.” Critically, zero papers in this cluster — or anywhere else in the reviewed literature — achieve the “Fully Coupled System” classification. The Kiirunavaara and Walenstadt programmes represent the empirical ceiling of what system-scale field testing can currently offer; converting that empirical ceiling into a transferable, mechanism-based numerical framework constitutes the central gap this review identifies.

### **3.4 Methodological Transfer: Data-Driven Calibration and High-Stress Cavern Analogues**

The final cluster (15 papers) does not address ground support directly. It comprises two related bodies of work — microseismic data processing and high-stress cavern stability analysis, predominantly from civil and hydropower engineering — included because their methodologies are directly transferable to the coupled, site-calibrated framework this review argues is currently missing.

#### **Microseismic data processing and calibration.**

Xu et al. (2025) present an automatic first-arrival-time picking method for microseismic signals based on fractal theory and feature fusion, directly relevant to real-time seismic-source characterization. Dai et al. (2025) develop a

microseismic criterion for dynamic risk assessment and early warning of roadway rockburst induced by coal mine seismicity. Neither study models a support system, but both demonstrate mature, field-validated methodologies for extracting the dynamic-loading parameters a coupled rock mass-support model would need as calibration input.

**High-stress cavern stability and splitting failure.**

Li, Zhang, and colleagues have produced a closely related series of studies on splitting failure in deep, high sidewall caverns: an initial complex-function and strain-gradient-based mechanistic treatment (Li et al., 2021, *Energies*), a subsequent analytical extension (Li et al., 2023), and a more recent finite-element-based failure simulation of a comparable cavern geometry (Li et al., 2025). Zhang et al. (2020) provide complementary physical model test data. Xu et al. (2025) perform an in-situ stress inversion study for a hydropower powerhouse excavation in southwest China. Tan et al. (2024), Pan et al. (2024), Huang et al. (2024), and Sudhakar et al. (2023) contribute further numerical and physical-model treatments of cavern stability in comparable high-stress settings.

**Thermal and cyclic loading analogues.**

Wu et al. (2025) examine the nonlinear failure criterion of hot dry rock under cyclic water-induced thermal shock, and Li et al. (2024) apply thermal-mechanical coupled peridynamic simulation to mode-I fracture in sandstone. Li, Yao, Liu, and Wang (2026) examine the damage mechanism of a deep ingate lining structure under cyclic blasting disturbance — notably one of the few papers in this cluster with a direct structural-support analogue, albeit in a civil rather than mining excavation context.

**Synthesis and rationale for inclusion.**

None of the 15 papers in this cluster achieve a classification above “Static Boundary” or “Uncoupled,” and the majority are classified as “No Support Modeled.” Their inclusion is justified not by their direct findings, but by the methodological transferability of their techniques — real-time seismic characterization, high-stress rock mass constitutive behaviour, and cyclic/dynamic loading treatment — that a coupled, site-calibrated ground support framework would need to draw upon.

**4. Critical Discussion: The Scale-and-Coupling Disconnect**

The preceding synthesis, organized deliberately by physical scale rather than by topic, author, or publication year, makes a pattern visible that a conventional topic-based literature review would likely obscure: across all 92 reviewed studies, spanning four conceptually distinct scales of analysis, not a single paper achieves what this review terms a “Fully Coupled System” — a numerical model in which rock mass, bolt, grout, mesh, and shotcrete interact dynamically as a single structural unit, calibrated against site-specific seismic demand. Table 2 makes this pattern explicit: every one of the 92 papers occupies one of eight lesser interaction-capability categories, and the “Fully Coupled System” row, populated only by this review’s own proposed framework, remains otherwise empty.

Table 2

Representative synthesis matrix classifying reviewed studies by physical scale, loading condition, methodology, and support-rock interaction capability.

| <b>Scale</b> | <b>Reference</b>                  | <b>Loading Condition</b> | <b>Methodology</b>      | <b>Interaction Capability</b> |
|--------------|-----------------------------------|--------------------------|-------------------------|-------------------------------|
| Rock-Mass    | He et al. (2012)                  | Dynamic                  | Analytical / Review     | No Support Modeled            |
| Rock-Mass    | Cai (2013)                        | Dynamic                  | Analytical / Conceptual | Conceptual                    |
| Rock-Mass    | Chai et al. (2017)                | Dynamic                  | Analytical              | No Support Modeled            |
| Rock-Mass    | Fuławka et al. (2022)             | Dynamic                  | Field                   | No Support Modeled            |
| Rock-Mass    | Cai (2024)                        | Dynamic                  | Review / Analytical     | Uncoupled                     |
| Rock-Mass    | Ding et al. (2026)                | Dynamic                  | Analytical / Review     | No Support Modeled            |
| Element      | Potvin & Hadjigeorgiou (2008)     | Static                   | Conceptual / Review     | Conceptual                    |
| Element      | Kaiser & Cai (2012)               | Dynamic                  | Conceptual / Analytical | Conceptual                    |
| Element      | Roth et al. (2014)                | Dynamic                  | Field + FEM             | Phenomenological              |
| Element      | Karampinos & Hadjigeorgiou (2021) | Static                   | Lab                     | Isolated Component            |
| Element      | Nguyen et al. (2019)              | Dynamic                  | FEM                     | Isolated Component            |
| Element      | Nozeres et al. (2021)             | Quasi-Static / Dynamic   | FEM                     | Isolated Component            |
| Element      | Wang et al. (2023)                | Dynamic                  | Lab (SHPB) + FEM        | Isolated Component            |
| Element      | Batan et al. (2025)               | Dynamic                  | Lab + FEM               | Isolated Component            |
| System       | Heal & Potvin (2007)              | Dynamic                  | Field                   | Empirical (No FEM)            |
| System       | Potvin & Wesseloo (2013)          | Dynamic                  | Conceptual / Analytical | Conceptual                    |
| System       | Shirzadegan (2014)                | Dynamic                  | Field (Methodology)     | Empirical (No FEM)            |
| System       | Saiang & Nordlund (2016)          | Static / Dynamic         | FEM                     | Phenomenological              |
| System       | Shirzadegan & Nordlund (2018)     | Dynamic                  | Field + FEM             | Phenomenological              |
| System       | Yi et al. (2021)                  | Dynamic                  | Field + FEM             | Phenomenological              |

| Scale          | Reference                               | Loading Condition                | Methodology                 | Interaction Capability      |
|----------------|-----------------------------------------|----------------------------------|-----------------------------|-----------------------------|
| System         | Nordström et al. (2020)                 | Dynamic (Seismic)                | Field / Statistical         | Empirical (No FEM)          |
| System         | Vallejos et al. (2024)                  | Dynamic                          | Field                       | Empirical (No FEM)          |
| System         | Shirzadegan et al. (2025)               | Dynamic                          | Field + FEM                 | Phenomenological            |
| System         | Gebremedhin et al. (2026)               | Dynamic                          | Field (In-Situ)             | Phenomenological            |
| Methodological | Zhang et al. (2020)                     | Static                           | Lab (Physical Model)        | No Support Modeled          |
| Methodological | Li et al. (2021, Energies)              | Static                           | Analytical                  | No Support Modeled          |
| Methodological | Xu, H. et al. (2025)                    | Microseismic                     | Data-Driven / Algorithmic   | N/A                         |
| Methodological | Dai et al. (2025)                       | Dynamic (Microseismic)           | Field / Statistical         | Uncoupled                   |
| Methodological | Li et al. (2025)                        | Static                           | FEM                         | Static Boundary             |
| Methodological | Li et al. (2026, ingate)                | Cyclic / Dynamic                 | FEM (LS-DYNA)               | Static Boundary             |
| —              | <b>This Review (Proposed Framework)</b> | <b>Dynamic (Site-Calibrated)</b> | <b>Field-Calibrated FEM</b> | <b>Fully Coupled System</b> |

### Restating the gap precisely.

It would be an overstatement to claim that system-level analysis of ground support is entirely absent from the literature: Section 3.3 demonstrates that large-scale field campaigns at Kiirunavaara and Walenstadt do test complete, installed support systems under genuine dynamic loading. The gap identified here is more precise and, for that reason, more actionable: the field lacks a generalized, mechanism-based numerical framework — as opposed to a site-specific phenomenological back-analysis — capable of predicting coupled rock-support dynamic performance under conditions other than those of the specific test from which the model was derived.

### Why the silo boundaries persist.

The scale-based organization of this review suggests the disconnect is not incidental but structural, arising from genuine differences in the modelling traditions, validation data, and computational demands native to each scale. Rock-mass-scale studies are typically validated against seismic monitoring networks and blast-vibration records, in which a fixed or absent support representation is an acceptable simplification. Element-scale studies are typically validated against laboratory load-displacement data from a single-component rig, in which representing the full complexity of a deforming, jointed rock mass would be computationally prohibitive at the fine mesh resolution such component-level models require. Reconciling these two traditions is nontrivial: a model with sufficient mesh resolution to capture bolt yielding in realistic detail becomes computationally intractable if extended across a rock mass volume large enough to capture genuine wave propagation — a scale-disparity problem that likely explains why the coupled framework identified here has not yet emerged despite being conceptually well motivated by multiple authors across both traditions (e.g., Potvin and Wesseloo, 2013; Cai, 2024).

## **The cost of an uncoupled rock mass boundary condition.**

The practical consequence of this disconnect is that current numerical predictions of dynamic support performance rest on an assumption — a static or simplified rock mass boundary — that is least defensible under precisely the conditions of greatest engineering interest. As mining depth increases, rock mass condition becomes an increasingly active contributor to how dynamic energy is transmitted to, and absorbed by, an installed support system, rather than a passive backdrop against which support response can be evaluated independently. A support element validated in isolation under an idealized rigid boundary condition may therefore perform differently — potentially significantly so — when installed in rock mass that is itself degrading dynamically under the same seismic event, a coupling effect that no reviewed element-scale study is currently positioned to predict.

## **Toward resolution: what the methodological-transfer literature offers.**

Section 3.4's inclusion of microseismic-calibration and high-stress-cavern literature is intended to demonstrate that the technical building blocks required to close this gap already exist, distributed across adjacent research communities rather than absent from the field entirely. Real-time microseismic source characterization (Xu et al., 2025; Dai et al., 2025) offers a pathway to deriving realistic, site-specific dynamic boundary conditions directly from an operating mine's existing seismic monitoring infrastructure. High-stress cavern constitutive and calibration approaches (the Li et al. series; Zhang et al., 2020) demonstrate mechanistic treatments of rock mass behaviour under extreme in-situ stress that could, in principle, be extended to incorporate an interacting support representation. What has not yet occurred, based on the 92 studies reviewed here, is the integration of these adjacent-field methodological advances with the element-scale constitutive sophistication of Section 3.2 and the site-calibration opportunity presented by ongoing programmes such as Kiirunavaara's.

## **Summary.**

The scale-and-coupling disconnect identified in this review is not a matter of any single research community lacking sophistication — each of the four scales reviewed here demonstrates genuine methodological advancement on its own terms. It is, rather, a structural gap between scales that has persisted because bridging it requires combining computational approaches, validation data, and constitutive assumptions that have so far developed largely independently. Section 5 proposes a modelling architecture intended to bridge this gap directly, using site-calibrated microseismic data as the mechanism by which rock-mass-scale demand and element-scale capacity can be coupled within a single dynamic simulation framework.

# **4.1 Positioning Relative to Existing Review Literature**

This review's dataset includes four existing review papers on closely adjacent topics (Wei et al., 2022; Waqar et al., 2023; Wu et al., 2022; He et al., 2022). Table 3 positions the present review against each, based on their published scope and stated focus, to clarify what is genuinely novel here rather than assert novelty without comparison.

Table 3

Positioning of this review relative to existing review papers on rockburst and ground support in the reviewed dataset.

| Review                        | Venue                       | Scope                                                                           | Organizing Principle                                                          | Focus                                                                                                                                               | Distinction from This Review                                                                                                                          |
|-------------------------------|-----------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wei et al. (2022)             | Int. J. Coal Sci. Technol.  | Ground support requirements in coal burst-prone mines                           | Support component type and selection procedure                                | Semi-analytical/empirical demand-capacity matching using laboratory test data, specific to coal mining                                              | Addresses support selection methodology, not numerical modelling scale-coupling; hard-rock dynamic FEM/DEM modelling is not central                   |
| Waqar, Guo & Qi (2023)        | Applied Sciences            | Rockburst mechanisms, prediction, and control strategies broadly                | Definitions/types → mechanisms → prediction → control                         | Rockburst hazard characterization; briefly notes a lab-to-field scale disconnect as an open challenge                                               | Does not organize by numerical modelling scale nor examine support-rock coupling; scale disconnect noted but not developed into a modelling framework |
| Wu, Ye, Wang & Hu (2022)      | Applied Sciences            | Development of rockburst research (methods, mechanism, classification, control) | Research theme / chronology                                                   | Rockburst research field development; ground support is one minor subsection within broader control measures                                        | Not a scale-based synthesis; support-rock numerical coupling not addressed                                                                            |
| He, Cheng, Qiao & Li (2022)   | J. Rock Mech. Geotech. Eng. | Rockburst experiments, theories, and simulations                                | Lab testing tech → influencing factors → theories/mechanisms → simulation     | Rockburst phenomenon itself (rock-mass side): lab testing methods, mechanisms, simulation of the burst event                                        | Simulation approaches concern rockburst occurrence/energy release, not ground support element or system dynamic modelling                             |
| <b>This Review (proposed)</b> | —                           | <b>Numerical modelling of ground support performance under dynamic loading</b>  | <b>Physical scale: rock-mass → element → system → methodological transfer</b> | <b>Diagnoses a specific support-rock coupling gap via a synthesis matrix; proposes a mechanism-based, microseismic-calibrated coupled framework</b> | <b>First scale-based synthesis to isolate and quantify the rock-support numerical coupling gap specifically</b>                                       |

As Table 3 shows, the four existing reviews address rockburst hazard characterization (Waqar et al., 2023; Wu et al., 2022; He et al., 2022) or ground support selection methodology in coal mining specifically (Wei et al., 2022). None organizes the literature by physical modelling scale, and none isolates or quantifies a rock-support numerical coupling gap as its central finding. Waqar et al. (2023) comes closest, briefly noting that reconciling laboratory- and field-scale rock mass behaviour remains an open challenge — a observation consistent with, but considerably less

developed than, the scale-and-coupling disconnect this review identifies and quantifies through its synthesis matrix (Table 2).

## 4.2 Research Gap Roadmap

Table 4 consolidates the specific gaps identified across Sections 3 and 4 into a single roadmap, linking each gap to its supporting evidence and the corresponding element of the framework proposed in Section 5.

Table 4  
Research gap roadmap linking identified gaps, supporting evidence, and proposed resolution.

| Identified Gap                                                   | Current State (Evidence)                                                          | Section Reference | Proposed Resolution                                                                                    |
|------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------------------------------|
| Rock-mass demand is modelled independent of support              | 20 of 22 rock-mass-scale papers have no support representation                    | Sections 3.1, 4   | Couple rock-mass domain directly with support representation (Section 5.1)                             |
| Element-scale capacity is tested in isolation from rock mass     | 33 of 37 element-scale papers classified 'Isolated Component'                     | Sections 3.2, 4   | Embed element constitutive models within a deforming rock mass domain (Section 5.1-ii)                 |
| System-scale field tests are phenomenological, not generalizable | Kiirunavaara/Walenstadt tests validate one site/configuration only                | Section 3.3       | Site-calibrate via microseismic data rather than a single deliberate test blast (Section 5.2)          |
| Dynamic boundary conditions are idealized or arbitrary           | Element-scale tests use lab-generated impact loading, not recorded seismic events | Sections 3.2, 5.2 | Derive boundary conditions from live/archived microseismic monitoring (Section 5.2)                    |
| No framework transferable across geology or support types        | Zero of 92 studies achieve 'Fully Coupled System' classification                  | Table 2, Fig. 4   | Staged validation: element calibration → rock mass calibration → system-level validation (Section 5.3) |

## 5. A Mechanism-Based Framework for Coupled Rock-Support Modelling

The critical discussion in Section 4 identifies a structural, scale-driven disconnect rather than a simple absence of research effort: closing it requires a modelling architecture explicitly designed to operate across the rock-mass and element scales simultaneously, rather than a further refinement within either scale in isolation. This section outlines such an architecture at a conceptual level, together with the validation pathway by which it could be developed and tested against real deep-mine conditions.

### 5.1 Modelling Architecture

The proposed framework couples three components within a single dynamic simulation environment:

- (i) A calibrated rock mass domain, representing the jointed, stressed rock volume immediately surrounding an excavation, parameterized using site-specific geomechanical data rather than the generalized or idealized rock properties typical of element-scale studies.

(ii) An explicit, non-idealized support representation, incorporating the constitutive behaviour already well established at the element scale – energy-absorbing bolt yielding, mesh rupture, shotcrete/TSL cracking – embedded directly within the rock mass domain rather than tested against a rigid boundary, allowing genuine two-way interaction.

(iii) A site-calibrated dynamic boundary condition, replacing the arbitrary or idealized velocity/pressure pulses common in current element-scale dynamic testing with an input derived directly from an operating mine's microseismic monitoring network.

Coupling these three components addresses the scale-disparity computational problem identified in Section 4 by explicitly limiting the high-resolution, element-scale mesh to the immediate support-rock interface, while representing the broader rock mass domain at a resolution sufficient to capture wave transmission and damage evolution – a graded-resolution strategy consistent with established multi-scale modelling practice, though one not yet applied to the specific rock-support coupling problem this review identifies.

## 5.2 Microseismic Calibration as the Coupling Mechanism

The central methodological innovation proposed here is the use of live or archived microseismic data – rather than an assumed or idealized dynamic pulse – as the framework's calibration input. Where Section 3.3's Kiirunavaara reanalyses have relied on a specific, deliberately generated test blast as their dynamic source, and Section 3.2's element-scale studies have relied on laboratory-generated impact loading, a microseismic-calibrated framework would instead derive its dynamic boundary condition from an actual recorded seismic event, characterized using techniques such as those demonstrated by Xu et al. (2025) and Dai et al. (2025). This approach removes reliance on the assumption that a deliberately generated test blast adequately represents naturally occurring mining-induced seismicity, and provides a mechanism for validating the coupled model against multiple recorded events of varying magnitude at a single site – directly addressing the transferability limitation identified in the Kiirunavaara reanalysis lineage.

## 5.3 A Staged Validation Pathway

Consistent with the applied, industry-linked research context motivating this review, the proposed framework is intended to be developed and validated through three linked stages:

1. Element-scale constitutive calibration, using existing and newly conducted laboratory dynamic testing of the specific bolt, mesh, and shotcrete/TSL products relevant to the target site.
2. Rock mass domain calibration, using site-specific geomechanical and in-situ stress data, informed by the constitutive and characterization approaches reviewed in Section 3.4.
3. System-level dynamic validation, comparing the coupled model's predicted support response against recorded field data from existing large-scale test programmes and, where available, against instrumented support response to genuine recorded seismic events.

## 5.4 Anticipated Contribution

If successfully developed, this framework would represent the first reviewed instance of a “Fully Coupled System” model in the sense defined by Table 2 – a numerical framework in which rock mass and support system interact dynamically as a single unit, calibrated against genuine site-specific seismic demand rather than an idealized or single-test-derived input. As deep hard-rock mines such as Kiirunavaara continue extending to greater depth and correspondingly elevated seismic hazard, a validated, mechanism-based tool for predicting – rather than only retrospectively reconstructing – ground support performance under site-specific dynamic demand would provide a substantially stronger basis for support design than currently available empirical or single-site phenomenological approaches allow.

## 6. Conclusion

This review has critically synthesized 92 studies addressing the numerical modelling of ground support performance under dynamic loading in deep hard-rock environments, identified through citation-network exploration and cross-validated against Scopus and Web of Science searches, with 86% of the final corpus independently verified against primary bibliographic sources. Rather than organizing this literature by topic, author, or chronology, the review adopted a physical-scale framework – rock-mass-scale demand, element-scale capacity, system-scale phenomenological testing, and methodologically transferable adjacent-field research – specifically to expose where modelling sophistication is concentrated and where it is absent. This structure revealed a consistent pattern across all four scales: dynamic demand characterization and element-scale support capacity have each advanced considerably, and large-scale field programmes at Kiirunavaara and Walenstadt have generated genuinely high-fidelity system-level empirical data – yet not a single reviewed study couples rock mass and support system as a single, dynamically interacting unit calibrated against generalizable, transferable site conditions.

This finding reframes what might otherwise appear to be simply “more research needed” into a specific, structural gap with an identifiable cause: the computational and validation traditions native to rock-mass-scale and element-scale modelling have developed largely independently because of a genuine scale-disparity problem, not because the need for coupling has gone unrecognized. The decade-long Kiirunavaara reanalysis lineage illustrates this gap with particular clarity – demonstrating that even sustained, high-quality field investment at a single site has not, on its own, produced a generalizable, mechanism-based modelling framework, because each successive study has necessarily been validated against the same specific test configuration rather than across varying geological and seismic conditions.

Bridging this gap, as outlined in the framework proposed in Section 5, does not require inventing new element-scale constitutive models or new rock-mass-scale wave-propagation theory – both are already well developed within the literature reviewed here. It requires, instead, the deliberate integration of these existing capabilities within a single coupled simulation, calibrated using site-specific microseismic data rather than idealized or single-test-derived dynamic inputs. As underground mines continue to extend toward greater depths and correspondingly elevated seismic hazard, the future reliability of ground support design in rockburst-prone conditions will depend less on further isolated advances at either the rock-mass or element scale, and more on the field's ability to finally couple the two.

## References

1. Baek, B. (2018). Behaviour of Welded Steel Wire Mesh as Surface Support.

2. Baek, B., Karampinos, E., Hadjigeorgiou, J. (2020). Understanding the Impact of Test Configuration on Welded-Wire Mesh Laboratory Test Results.
3. Batan, C.K. et al. (2024). Assessment of the Performance of Ground Support System in Burst-Prone Areas.
4. Batan, C.K. et al. (2025). Numerical modelling of drop mass shape influence on energy absorption of welded wire mesh in dynamic impact conditions.
5. Cai, M. (2013). Principles of rock support in burst-prone ground.
6. Cai, M. (2024). Rockburst Risk Control and Mitigation in Deep Mining.
7. Chai, S. et al. (2017). Theoretical study for induced seismic wave propagation across rock masses during underground exploitation.
8. Chai, S. et al. (2020). Numerical Study of Ground Vibrations Caused by Cylindrical Wave Propagation in a Rock Mass with a Structural Plane.
9. Chen, L., Li, Q., Yang, J., Qiao, L. (2018). Laboratory Testing on Energy Absorption of High-Damping Rubber in a New Bolt for Preventing Rockburst in Deep Hard Rock Mass.
10. Dai, L. et al. (2025). Microseismic criterion for dynamic risk assessment and warning of roadway rockburst induced by coal mine seismicity.
11. Deng, J. et al. (2025). Induced Mechanism of Tunnel Rockbursts Based on Dynamic Buckling of Plates.
12. Ding, C. et al. (2026). Research progress and future prospect of blasting theory and technology for deep rock masses: A review primarily based on Chinese perspectives.
13. Eremenko, A.A. et al. (2024). Features of rock mass geodynamics during large-scale blasting in rockburst-hazardous iron ore mining.
14. Fuławka, K. et al. (2022). Seismic evaluation of the destress blasting efficiency.
15. Gebremedhin, B., Mikula, P., Darlington, B., Sarmadivaleh, M. (2026). Dynamic Ground Support Behaviour Assessed Through Higher Order Dynamic Parameters and Time Metrics.
16. Hanumanthappa, M., Maji, V. (2017). Empirical and Numerical Analyses of Tunnel Closure in Squeezing Rock.
17. Hao, L. et al. (2018). Dynamic Model and Mechanical Properties of the Two Parallel-Connected CRLD Bolts Verified with the Impact Tensile Test.
18. He, M. et al. (2012). Studies on classification, criteria and control of rockbursts.
19. He, M. et al. (2014). Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance.
20. He, M. et al. (2017). Dynamic tests for a Constant-Resistance-Large-Deformation bolt using a modified SHTB system.
21. He, M. et al. (2022). A review of rockburst: Experiments, theories, and simulations.
22. Heal, D., Potvin, Y. (2007). In-situ dynamic testing of ground support using simulated rockbursts.
23. Huang, T. et al. (2024). A physical model test for the stress and deformation analyses in underground caverns containing block during excavation.
24. Kabwe, E. (2023). Performance of dynamic reinforcements to restrain remote triggered strainburst associated failure.
25. Kaiser, P.K., Cai, M. (2012). Design of rock support system under rockburst condition.
26. Kang, H. et al. (2021). A combined “ground support-rock modification-destressing” strategy for 1000-m deep roadways in extreme squeezing ground condition.

27. Kang, H. et al. (2021). Experimental Study on the Performance of Different Meshes Under Quasi-Static Loading.
28. Karampinos, E., Baek, B., Hadjigeorgiou, J. (2018). Discrete element modelling of a laboratory static test on welded wire mesh.
29. Karampinos, E., Hadjigeorgiou, J. (2020). Quantifying the Impact of Bolting Patterns on the Performance of Welded Wire Mesh.
30. Karampinos, E., Hadjigeorgiou, J. (2022). The Influence of Bolt Density on Welded Wire Mesh Performance.
31. Khaleghparast, S. et al. (2023). An experimental study on shear behaviour of fully grouted rock bolt under static and dynamic loading conditions.
32. Li, F. et al. (2021). Failure Mechanism and Numerical Simulation of Splitting Failure for Deep High Sidewall Cavern Under High Stress.
33. Li, F. et al. (2023). Investigating the mechanism of splitting failure in deep high sidewall cavern based on complex function and strain gradient.
34. Li, F., Zhang, Q., Xiang, W. (2021). Mechanism of Splitting Failure for High Sidewall Cavern of Hydropower Station Based on Complex Function and Strain Gradient.
35. Li, F., Zhang, Q., Xin, G., Long, G., Dong, Y. (2025). Failure Mechanism and Numerical Simulation of Splitting Failure for Deep High Sidewall Cavern under High In-situ Stress.
36. Li, H. et al. (2024). Thermal effects on mode I fracture of sandstone: Accurate crack identification in thermal-mechanical coupled peridynamic simulations.
37. Li, X., Yao, Z., Liu, X., Wang, X. (2026). Study on the damage mechanism of deep ingate lining structure disturbed by cyclic blasting.
38. Liu, X. et al. (2024). Excavation response and reinforcement practice of large underground caverns within high-stress hard rock masses: The case of Shuangjiangkou hydropower Station, China.
39. Lu, Z. et al. (2017). Numerical Simulation of Fragment Separation during Rock Cutting Using a 3D Dynamic Finite Element Analysis Code.
40. Masoudi, R., Sharifzadeh, M. (2018). Reinforcement selection for deep and high-stress tunnels at preliminary design stages using ground demand and support capacity approach.
41. Mombilia, F.M.M. et al. (2025). Analytical dataset to determine squeezing potential of deep tunnels.
42. Nguyen, B., Cai, M., Challagulla, K. (2018). Finite Element Analysis Of Modified Conebolt Under Static And Dynamic Loadings.
43. Nguyen, B., Cai, M., Challagulla, K. (2019). Finite element analysis of the Superbolt under dynamic loading.
44. Nielsen, K.L., Niordson, C.F. (2019). A finite strain FE-Implementation of the Fleck-Willis gradient theory: Rate-independent versus visco-plastic formulation.
45. Nordström, E., Dineva, S., Nordlund, E. (2020). Back Analysis of Short-Term Seismic Hazard Indicators of Larger Seismic Events in Deep Underground Mines (LKAB, Kiirunavaara Mine, Sweden).
46. Nozeres, F. et al. (2021). Numerical modelling strategies using implicit and explicit methods to simulate quasi-static and dynamic three-points bend fracture tests of a ductile steel.
47. Pan, P. et al. (2024). A three-dimensional numerical study on the stability of layered rock spillway tunnel in alpine canyon areas.
48. Potvin, Y. (2017). The need for new technology to optimise the engineering design of ground support systems in underground mines.

49. Potvin, Y., Hadjigeorgiou, J. (2008). Ground support strategies to control large deformations in mining excavations.
50. Potvin, Y., Hadjigeorgiou, J. (2008). International Symposium on Ground Support in Mining and Civil Engineering Construction.
51. Potvin, Y., Wesseloo, J. (2013). Towards an understanding of dynamic demand on ground support.
52. Pytlik, A., Prusek, S., Masny, W. (2016). A methodology for laboratory testing of rockbolts used in underground mines under dynamic loading conditions.
53. Roth, A. et al. (2014). Analysis and numerical modelling of dynamic ground support based on instrumented full-scale tests.
54. Saadatmand Hashemi, A., Katsabanis, P. (2020). The Effect of Stress Wave Interaction and Delay Timing on Blast-Induced Rock Damage and Fragmentation.
55. Saiang, D., Nordlund, E. (2016). Ground support modelling involving large ground deformation: Simulation of field observations – Part 1.
56. Schubert, W. (2004). Tunnelling in Alpine Fault Zones Excavation and Support Strategies.
57. Sengani, F. (2021). A short note on the performance of steel-welded mesh under static loading.
58. Shirzadegan, S. (2014). Development of a methodology for in-situ dynamic testing of ground support.
59. Shirzadegan, S., Nordlund, E. (2018). Numerical Analysis of the Large Scale Dynamic Tests of Rock Support at LKAB Kiirunavaara.
60. Shirzadegan, S., Nordlund, E., Zhang, P. (2016). In-situ dynamic testing of rock support at LKAB Kiirunavaara mine.
61. Shirzadegan, S., Nordlund, E., Zhang, P. (2016). Large Scale Dynamic Testing of Rock Support System at Kiirunavaara Underground Mine.
62. Shirzadegan, S., Warema, S., Nordlund, E., Zhang, P., Yi, C. (2025). Numerical Analysis of the Large-scale Dynamic Test of Rock Support at Kiirunavaara mine – Improved Design.
63. Stacey, T. (2011). Support of Excavations Subjected to Dynamic (Rockburst) Loading.
64. Stacey, T. (2012). A philosophical view on the testing of rock support for rockburst conditions.
65. Stacey, T. (2016). Addressing the Consequences of Dynamic Rock Failure in Underground Excavations.
66. Sudhakar, K. et al. (2023). Study on the Impact of Different Parameters on Prediction of Crown Deformations in Underground Caverns.
67. Tan, F. et al. (2024). Integrated approach of predicting rock stability in high mountain valley underground caverns.
68. Tang, J., Li, T., Zeng, P. (2024). Rockburst-Specific Flexible Protection Net (RFPN) for Tunnels: Creation, Characteristics, and Preliminary Application.
69. Tao, Z. et al. (2016). Support principles of NPR bolt/cable and control techniques of large-deformation disasters.
70. Vallejos, J. et al. (2019). Progress in the numerical modelling of dynamic testing for reinforcement and retaining elements used in underground excavations.
71. Vallejos, J.A. et al. (2023). Dynamic Test Response of Ground Support Systems for Underground Excavations at the Walenstadt Testing Facility.

72. Wang, L. et al. (2022). Effective velocity of reflected wave in rock mass with different wave impedances of normal incidence of stress wave.
73. Wang, S., Wang, J., Xiong, X., Ren, Z., Weng, L., Khandelwal, M., Zhou, J. (2023). Dynamic compression mechanical properties of sandstone supported by Thin Spray-On Liner.
74. Waqar, M. et al. (2023). A Comprehensive Review of Mechanisms, Predictive Techniques, and Control Strategies of Rockburst.
75. Warema, S. (2026). Numerical evaluation of rock supports performance from a large-scale blasting test at Kiirunavaara Mine, Sweden.
76. Wei, C. et al. (2022). A review of investigations on ground support requirements in coal burst-prone mines.
77. Whiting, R. (2017). In situ static performance assessment of mine mesh.
78. Wu, M. et al. (2022). Development of Rockburst Research: A Comprehensive Review.
79. Wu, X. et al. (2025). Experimental study on nonlinear failure criterion of HDR under cyclic water-induced thermal shock.
80. Wu, Y. et al. (2019). Experimental Study on the Performance of Rock Bolts in Coal Burst-Prone Mines.
81. Xie, Z. et al. (2024). A New Approach to Designing Advance Stress Release Boreholes to Mitigate Rockburst Hazards in Deep Boring-Machine-Constructed Tunnels.
82. Xu, H. et al. (2025). Automatic Picking Method for the First Arrival Time of Microseismic Signals Based on Fractal Theory and Feature Fusion.
83. Xu, X. et al. (2025). Inversion Study of In-Situ Stress in the Underground Powerhouse Area of a Large Hydropower Project in Southwest China.
84. Yang, F. et al. (2025). Surrounding rock deformation characteristics and control strategies during passing through abandoned roadway group.
85. Yang, W. et al. (2024). Study on Static and Dynamic Tests of Polyester Fiber Flexible Protection Nets for Rock Burst.
86. Yi, C., Nordlund, E., Zhang, P., Warema, S., Shirzadegan, S. (2020). Numerical modeling for a simulated rockburst experiment using LS-DYNA.
87. Yi, C., Zhang, P., Nordlund, E., Shirzadegan, S., Nyberg, U. (2016). Numerical modelling of dynamic response of underground openings under blasting based on field tests.
88. Yu, S. et al. (2021). Destressing Mechanics Effect of Surrounding Rock Induced by Blasting Precondition at Deep Drift Development.
89. Yuan, A. et al. (2025). Study on dynamic and static load characteristics and rockburst induced mechanism under the influence of fault.
90. Zhang, P., Yi, C., Nordlund, E., Shirzadegan, S., Nyberg, U. (2013). Numerical back-analysis of simulated rockburst field tests by using coupled numerical technique.
91. Zhang, Q. et al. (2020). Experimental investigation on splitting failure of high sidewall cavern under three-dimensional high in-situ stress.
92. Zou, Y. et al. (2025). Numerical assessment of the influence of residual rock mass properties on destress blasting in deep mine.

## Figures

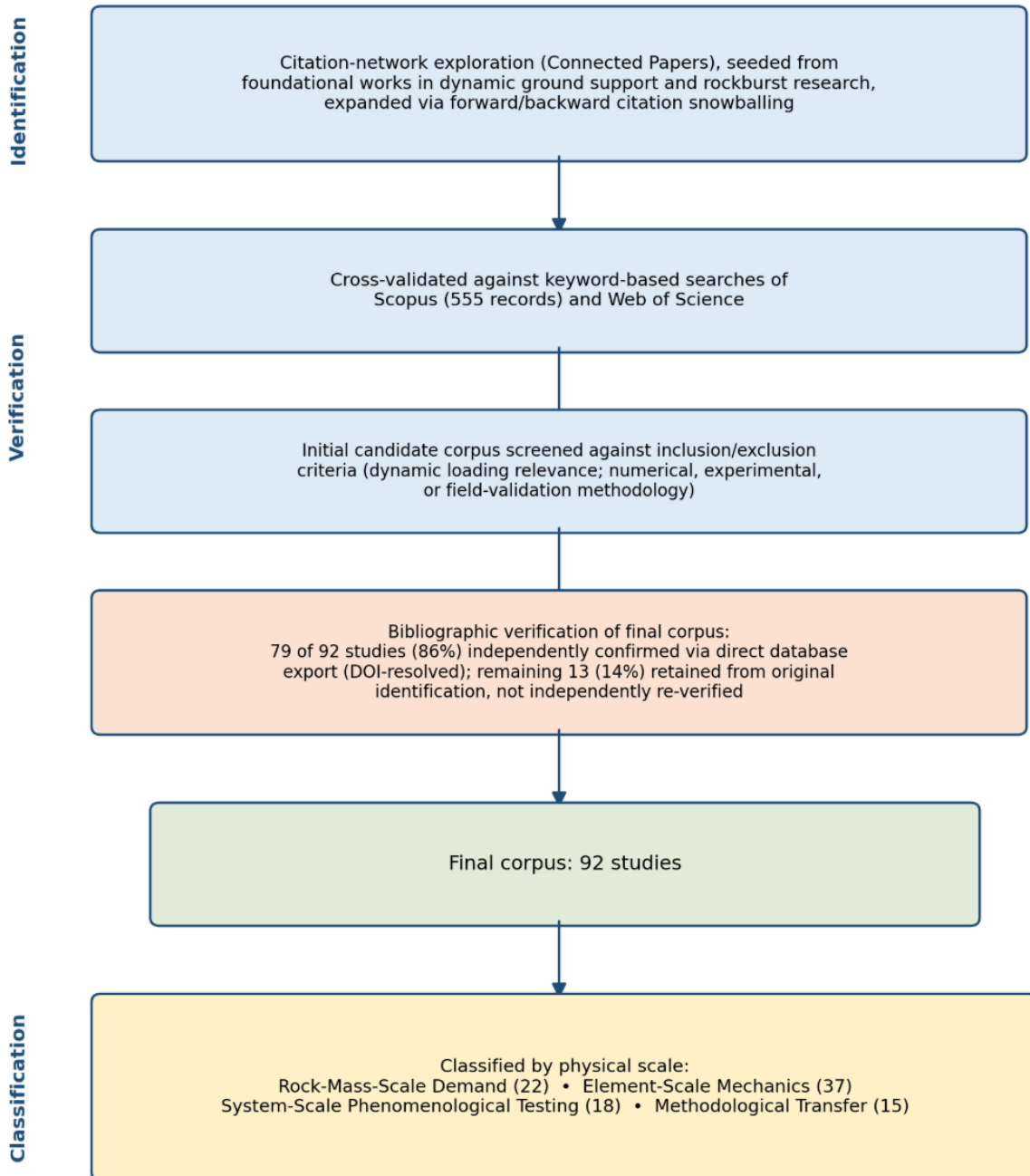


Figure 1

Literature identification, verification, and classification process.

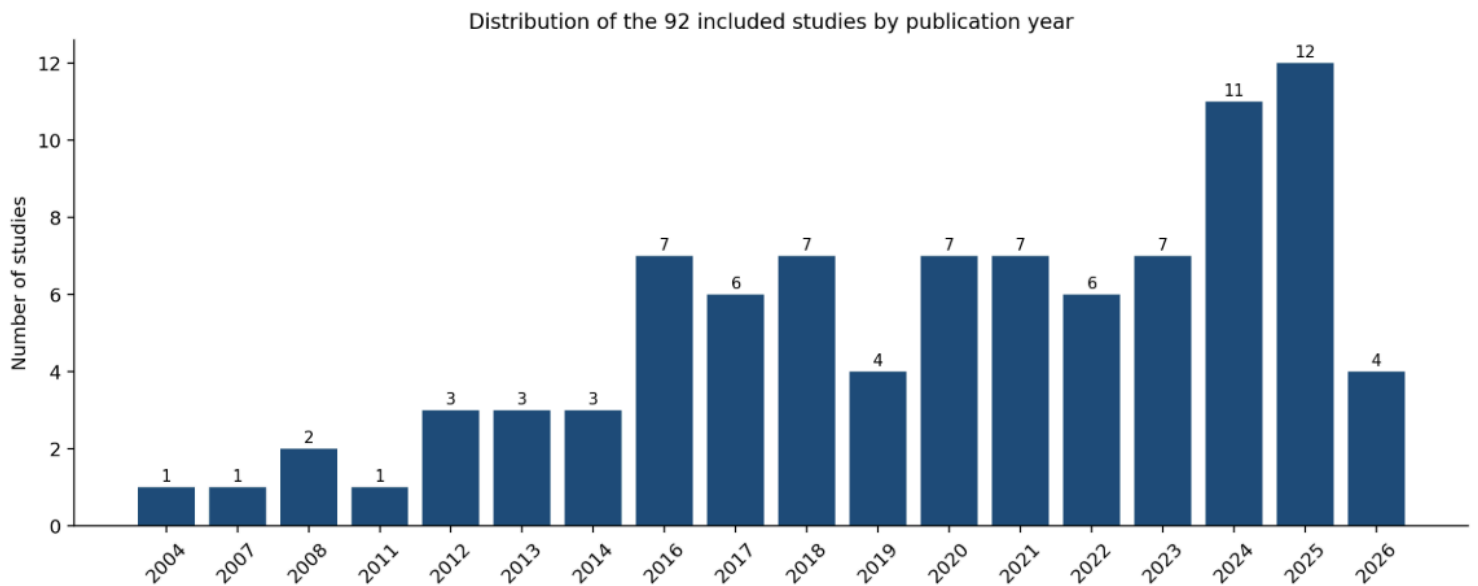


**Figure 2**

**Distribution of the 92 included studies by publication year, illustrating the recency and growth of this literature.**

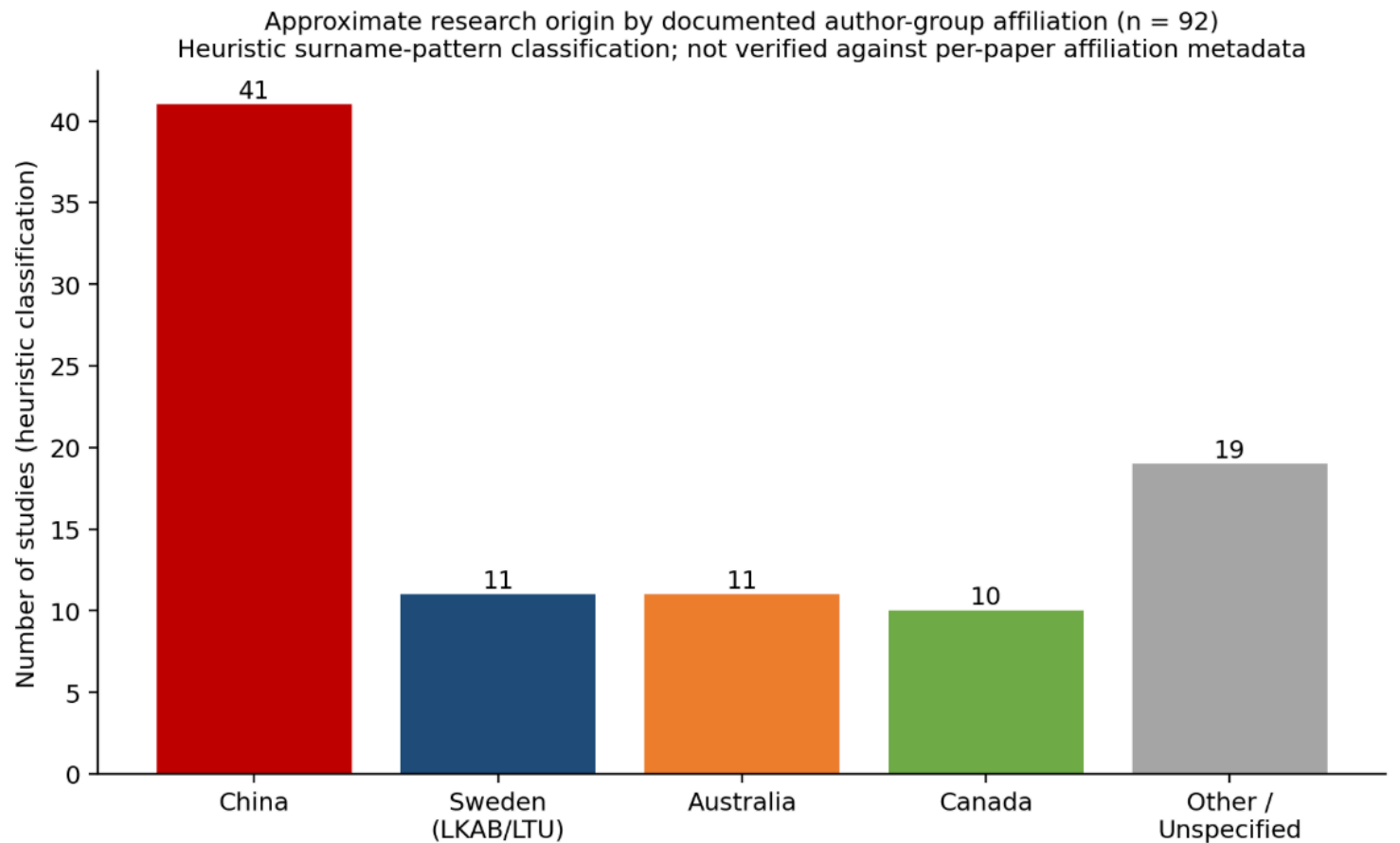


**Figure 3**

**Approximate geographic distribution of research origin across the 92 included studies, based on a heuristic classification of documented author-group affiliations (e.g., the Kiirunavaara test series to Luleå University of**

Technology, Sweden; Potvin, Hadjigeorgiou, and Cai to Australian and Canadian research groups). This classification was not independently verified against per-paper affiliation metadata and should be treated as illustrative rather than definitive.

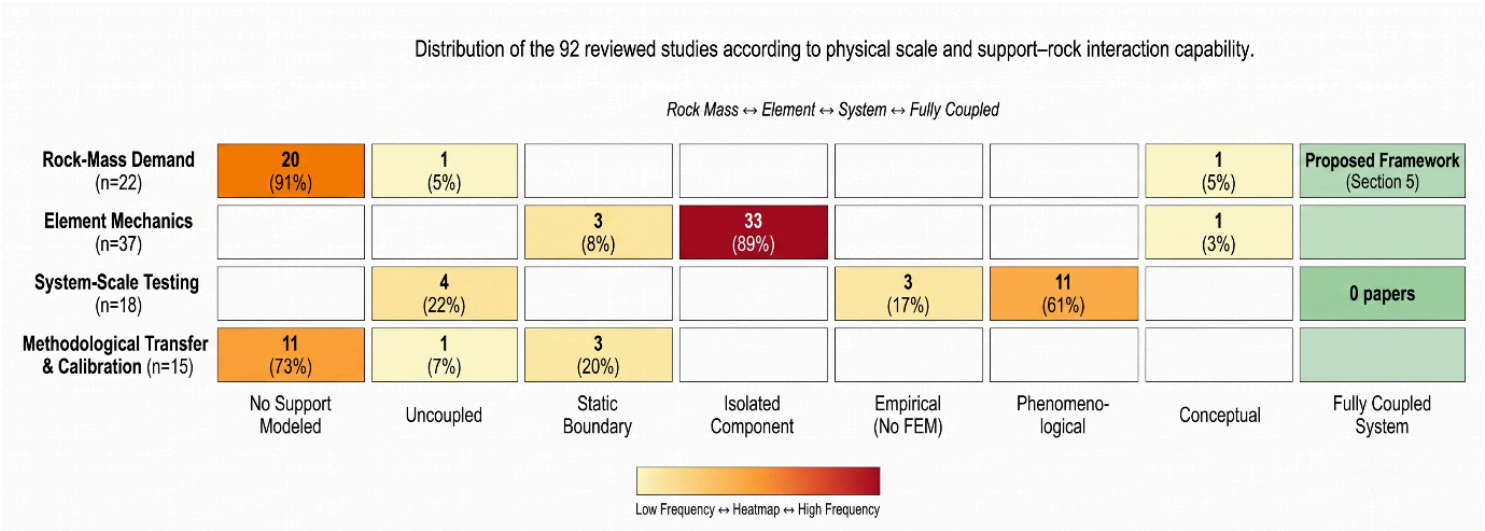


Figure 4

Support-rock interaction capability by physical scale across all 92 reviewed studies. The 'Fully Coupled System' category is empty across every scale.

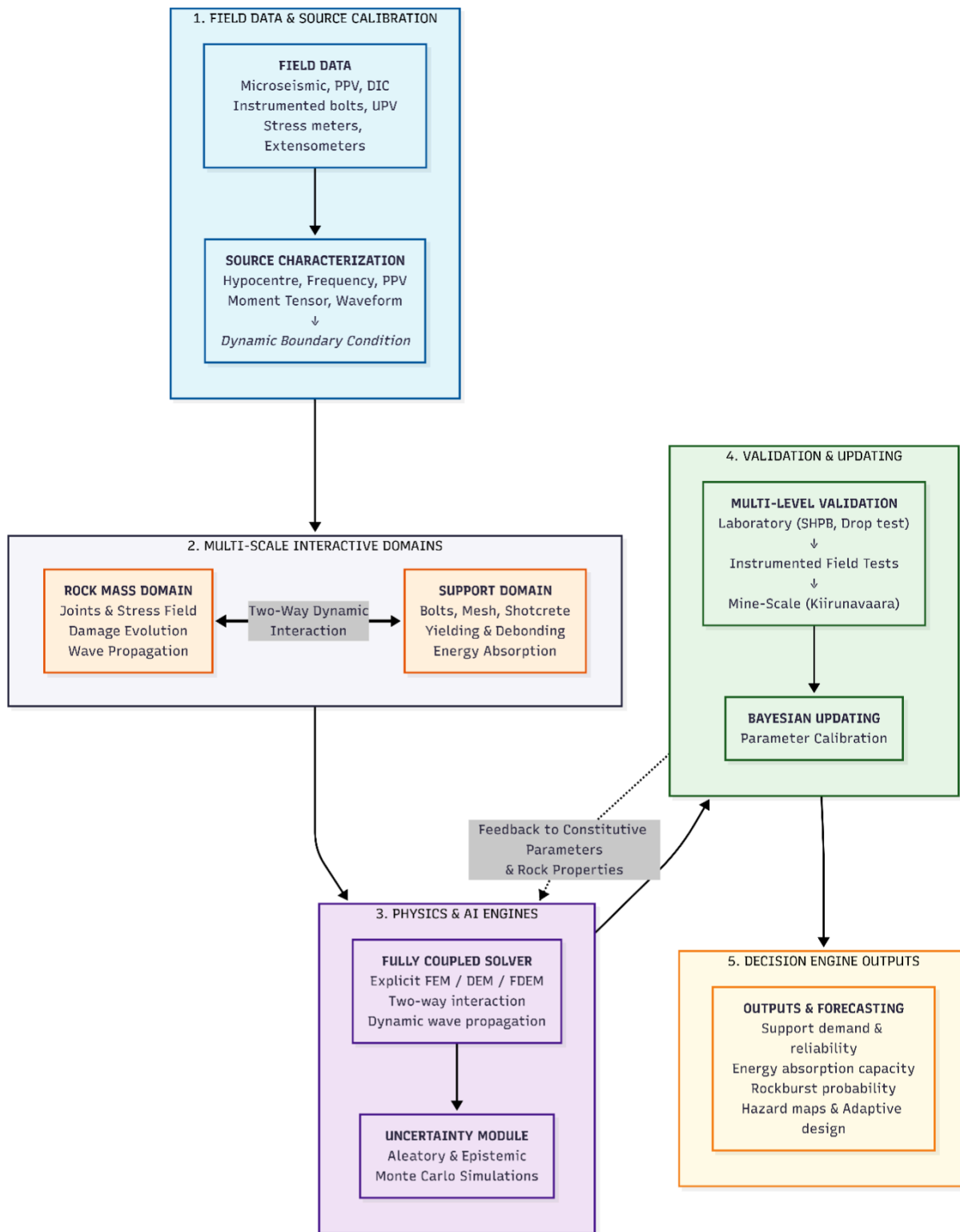


**Figure 5**

**Proposed mechanism-based, site-calibrated coupled modelling architecture.**