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Editorial

Rock Mechanics Development Driven by Multiscale Coupling and Engineering Practice: New Ideas and New Horizons

Chun Zhu [1,2], Ming Huang [2], Shibin Tang [3], Rui Huang [4,*], Shengyuan Song [5], Susheng Wang [1] and Haiqing Yang [6]

[1] State Key Laboratory of Intelligent Deep Metal Mining and Equipment, Shaoxing University, Shaoxing 312000, China
[2] School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China
[3] School of Civil Engineering, Dalian University of Technology, Dalian 116024, China
[4] International Scientific and Technological Cooperation Base for Geological Disaster Prevention of Zhejiang Province, Shaoxing University, Shaoxing 312000, China
[5] College of Construction Engineering, Jilin University, Changchun 130026, China
[6] School of Civil Engineering, Chongqing University, Chongqing 400045, China
* Correspondence: zjuhr@foxmail.com

1. Introduction

Rock mechanics was developed to solve stability, failure and fragmentation problems in rock engineering, yet its subject remains one of the most complex materials in civil, mining, energy and geological engineering. Natural rock masses contain bedding, joints, cleats, pores, mineral fabrics, healed fractures and weathered interfaces, distributed irregularly from the grain scale to the engineering scale. Their response is further shaped by high in situ stress, groundwater, temperature, chemical reactions, excavation disturbance and time-dependent deformation. This complexity explains why rock mechanics draws on solid mechanics, soil mechanics, engineering geology, mining engineering and computational science rather than a single disciplinary theory. Its central task is not only to measure rock properties, but also to express structural uncertainty, identify dominant mechanisms and transform unstable geological media into analyzable and controllable engineering systems.

Structured and fractured rock masses pose a core challenge because their strength and failure are governed by the geometry, persistence and activation of internal discontinuities. Bedding, schistosity and joint sets make strength dependent on loading direction, confining pressure and weakness-plane activation. Experimental and numerical studies have established strength criteria for anisotropic and jointed rocks and clarified the deformation of stratified rock masses in tunneling [1–3]. The intermediate principal stress and columnar joint geometry can further reshape strength envelopes and failure paths [4–6]. At the fracture scale, hydromechanically coupled and phase-field models capture non-planar hydraulic fracture propagation, fracture nucleation and rate-dependent fracture growth [7–9]. Mesoscale and fracture-scale simulations also indicate that material heterogeneity and pre-existing fractures influence crack propagation paths [10,11]. These findings suggest that structural planes are organizing elements that control damage initiation, localization and engineering instability.

Water–rock–stress coupling links mechanical stability with pore-scale transport, chemical reactions and environmental safety in fractured and porous rocks. In fractured carbonate rocks, acid dissolution can enlarge apertures and redirect flow, although dissolution at contacting asperities may also promote fracture closure and reduce permeability [12,13]. Carbonate content, rock texture and fracture roughness further influence transmissivity

Check for updates

Received: 9 October 2026
Accepted: 19 October 2026
Published: 24 October 2026

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and acid-etching patterns [14]. Mineral suspension and dissolution can also alter strength and compressibility in soft carbonate rocks [15]. In fracture networks, flow partitioning at intersections and stress-induced closure influence solute transport [16,17]. Field injection tests provide estimates of fracture aperture variability and relative permeability [18], while ultrasonic measurements combined with X-ray CT help characterize progressive fracture damage in carbonate rocks [19]. Studies of shale–fluid interactions, CT-based sandstone models and ultrasonic responses across filled joints further show how pore fluids, stress, clay minerals and saturation affect transport behavior and monitoring signals [20–22]. Saturation-dependent wave velocity correlations suggest that geophysical signals can constrain strength and damage state when calibrated against rock type and water content [23].

Engineering construction places rock mass behavior in direct interaction with tunnels, roadways and support systems, where excavation disturbance and reinforcement jointly control stability. In underground openings, drill-and-blast excavation generates dynamic cracks and vibrations, making delay timing, vibration characterization and modeling of rock fragmentation important for understanding and controlling excavation damage [24–26]. In fractured or water-rich ground, grouting reinforcement has shifted from empirical sealing toward mechanistic analysis of coupled deformation, non-Darcy seepage and obstruction-controlled grout diffusion [27–29]. Intelligent inversion of surrounding rock parameters, combined with three-dimensional numerical modeling, can inform support optimization for underground excavations; a study of a water diversion surge shaft demonstrated that incorporating long anchor cables reduced surrounding-rock deformation and limited plastic-zone development [30]. Dynamic hazards also require attention, as shaking table tests and energy-absorbing support systems show that void interaction, seismic loading and impact disturbance can alter underground structural damage modes [31,32].

Underground energy storage, wellbore drilling and cold-region geotechnics extend rock mechanics to long-term safety under coupled and evolving boundary conditions. Salt cavern gas storage requires tightness evaluation of cap rocks and interlayers in bedded salt formations, because their permeability governs potential leakage pathways and sealing reliability [33]. Coal and shale drilling require stability models that consider weakness patches, bedding and anisotropic fracture toughness, since continuum assumptions may underestimate collapse risk and trajectory sensitivity [34,35]. Frozen soils introduce another coupling mechanism: unfrozen water, suction and phase change influence thermal, hydraulic and mechanical behavior in cold-region foundations, tunnels and slopes [36]. Across these applications, a rock mass is not a fixed material with constant parameters, but an evolving system whose states are altered by engineering operations. Future progress depends on integrating testing, monitoring, modeling and field feedback to translate complex mechanisms into robust design and risk-control strategies.

2. Special Issue Content

The papers in this Special Issue make coordinated contributions to the understanding and solution of complex rock mechanics problems. Triaxial testing, digital core imaging, CT scanning, acoustic emission monitoring, ultrasonic transmission experiments, phase-field modeling, pore-scale reconstruction, theoretical analysis, numerical simulation and field validation are combined across the collection. This methodological diversity reflects the nature of the topic itself: rock engineering stability depends on the coupling of structure, stress, water, temperature, time and construction disturbance, and therefore requires evidence from multiple scales and disciplines. By bringing together laboratory observation, theoretical interpretation, numerical modeling and engineering verification, this Special

Issue highlights the need to understand rock masses as evolving systems rather than as isolated materials under a single-factor control.

In the field of rock mass structure, strength and fracture mechanisms, several studies provide new insight into the failure of heterogeneous or anisotropic rocks. Comparative evaluation of anisotropic strength criteria under different bedding orientations and confining pressures shows that failure may shift among bedding-parallel sliding, cross-bedding shear and hybrid mechanisms (contribution 1). Real-time CT scanning and acoustic emission monitoring further reveal self-organized criticality and yield-stage precursors during sandstone fracture, providing a possible basis for instability prediction (contribution 2). Fracture competition and non-planar propagation in crystalline rocks are also clarified through a hydro-mechanical phase-field model, which demonstrates the controlling role of grain-scale heterogeneity in fracture paths, pressure evolution and local failure modes (contribution 3). Together, these studies strengthen the mechanical expression of rock structure, clarify the transition from microscopic damage to macroscopic failure, and provide a more detailed basis for interpreting instability processes in structurally complex rock masses.

In the field of water–rock–stress coupling, pore-scale transport and environmental rock mechanics, the collected papers show how fluid and pore structures reshape engineering behavior. Three-dimensional digital core imaging, dissolution experiments and reactive numerical simulation are used to examine the interaction between phosphogypsum leachate and carbonate rocks, highlighting the role of fracture aperture and preferential flow in karst dissolution (contribution 4). The Quartet Structure Generation Set method is used to reconstruct rock pore structures and quantify how porosity, pore distribution, water saturation and temperature affect radon diffusion and permeability (contribution 5). Under dry and saturated conditions, ultrasonic wave transmission experiments link igneous-rock saturation, pore–fracture development and acoustic signal attenuation (contribution 6). These studies extend rock mechanics from strength evaluation to coupled migration, detection and environmental safety assessment, emphasizing that fluid transport, pore evolution and physical signal response are integral to the assessment of rock engineering behavior.

In engineering control, construction disturbance and rock mass reinforcement, this Special Issue presents practical solutions for mines, tunnels, slopes and underground excavations. Directional blasting in prefabricated grooved concrete shows that vertical stress can improve crack guidance and stabilize propagation velocity (contribution 7). For deep multi-coal seam mining, a hierarchical deep-hole blasting scheme integrates theoretical analysis, numerical optimization and field testing to achieve roof cutting, pressure relief and roadway protection (contribution 8). Weakly cemented sandstone reinforcement is addressed through silica sol grouting, where micro- and nano-pore filling reduces permeability while improving strength and deformation resistance (contribution 9). Rock slope stability is examined through comparative two- and three-dimensional limit-equilibrium analyses, highlighting the influence of spatial discontinuities on stability assessment and anchorage design (contribution 10). These papers connect rock dynamics, soft rock mechanics and support optimization, providing actionable technologies for deformation control and safe excavation while demonstrating how disturbance management and reinforcement design can be integrated into practical rock engineering strategies.

In underground energy, wellbore stability, mining-induced disturbance and cold-region geotechnics, the contributions further broaden the engineering scope of complex rock mechanics. Micro-leakage control in underground salt cavern gas storage is evaluated through different plugging methods, leading to a combined brine crystallization and ultrafine cement grouting solution with low permeability and adequate strength (contribution 11). Coal seam wellbore instability is analyzed by coupling weakness-plane strength criteria with wellbore stress, revealing how bedding, face cleats and butt cleats

influence collapse risk (contribution 12). The freezing behavior of unsaturated soils is clarified by examining the effects of boundary conditions, sample scale and soil type on supercooling and freezing temperatures (contribution 13). Dynamic disturbance of thick and hard mining overburden is investigated through physical similarity modeling, revealing fracture–migration behavior and the stabilizing effect of roof pre-splitting (contribution 14). These studies address long-term safety, drilling risk and thermal–hydraulic–mechanical behavior in settings where conventional rock mechanics assumptions are often insufficient, and they further illustrate the importance of adapting rock mechanics concepts to energy storage, resource extraction and cold-region engineering conditions.

3. Closing Remarks

This Special Issue systematically reviews and extends current research on complex rock mechanics problems and their engineering solutions. The collected papers highlight advances in anisotropic rock strength, fracture prediction, water–rock–stress coupling, pore-scale migration, controlled blasting, grouting reinforcement, underground storage tightness, wellbore stability and frozen ground behavior. These topics align closely with the strategic needs of deep resource extraction, safe underground construction, low-carbon energy storage, disaster prevention and intelligent geotechnical infrastructure.

While substantial progress has been achieved, the papers also show that future rock mechanics must move beyond isolated tests or single-field models. The most urgent problems arise from interactions among structural planes, stress redistribution, seepage, chemical reactions, dynamic disturbance, thermal effects and long-term deformation. Addressing these problems will require stronger integration of high-resolution testing, real-time monitoring, multi-field numerical simulation, computer-aided design and engineering feedback systems. In this sense, this Special Issue not only summarizes recent achievements but also points toward a more systematic and solution-oriented framework for rock mechanics.

Overall, the studies gathered here advance both the theoretical and practical frontiers of rock engineering. By linking mechanism identification with design optimization and field application, they provide useful guidance for improving the safety, efficiency and sustainability of tunnels, mines, caverns, reservoirs, slopes, wellbores and other rock engineering systems. The continuing development of complex rock mechanics will depend on this same balance between scientific depth and engineering usability: models must become more faithful to geological reality, and solutions must become more robust under uncertainty.

Author Contributions: Investigation: S.W., R.H. and S.S.; validation: C.Z. and H.Y.; writing—original draft preparation: C.Z. and M.H.; writing—review and editing: R.H. and S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by State Key Laboratory of Intelligent Deep Metal Mining and Equipment, Shaoxing University (NO. SXUIDME2601) and International Scientific and Technological Cooperation Base for Geological Disaster Prevention of Zhejiang Province (NO. IBGDP-2022-02).

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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