International Journal of Mining Science and Technology 36 (2026) 1925–1927

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Guest editorial to the special issue polar geotechnical engineering and environmental protection

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1. Introduction

Global climate change and the growing demand for sustainable resource development are bringing unprecedented attention to the Earth's cryosphere [1]. The Arctic, Antarctic, the Third Pole (the Qinghai–Xizang Plateau), and other polar-like cold regions are not only sensitive indicators of climate change but also strategic regions for scientific exploration, infrastructure development, and natural resource utilization [2]. Rapid environmental change is reshaping these fragile environments, posing increasing challenges to engineering safety, ecological conservation, and the sustainable coexistence of human activities and the natural environment. Consequently, polar geotechnical engineering and environmental protection have become increasingly important research frontiers that require close integration of geoscience, engineering, and environmental science.

The evolution of polar environments is fundamentally changing the behavior of frozen geomaterials and the stability of engineering systems. Permafrost degradation, glacier retreat, and intensified freeze–thaw processes alter the thermal, hydraulic, and mechanical properties of soils and rocks, while accelerating the development of geological hazards such as rockfalls, landslides, ice avalanches, and glacial lake outburst floods [3]. These complex processes are governed by coupled thermo–hydro–mechanical interactions across multiple spatial and temporal scales, presenting significant challenges for understanding polar geotechnical behavior, hazard assessment, infrastructure resilience, and environmental management. Addressing these challenges requires not only a better understanding of the underlying physical mechanisms but also advances in field observation, laboratory testing, numerical modelling, intelligent monitoring, and engineering technologies.

This special issue aims to advance the understanding of geotechnical processes and engineering challenges in polar environments, while encompassing the Third Pole and other polar-like cold regions where similar cryogenic processes govern engineering behavior. The 13 contributions included in this issue cover three interconnected themes: the mechanical behavior and evolution of polar geotechnical materials, the mechanisms and assessment of polar-related geohazards, and emerging technologies for engineering exploration under extreme cold conditions. These studies provide new insights into the response of geotechnical systems affected by low temperature, ice-related processes, and environmental change, contributing to safer, more resilient, and sustainable engineering practices in polar and cold-region environments.

2. Polar geotechnical materials

Frozen soils and cold-region rocks constitute the principal geomaterials in polar geotechnical engineering. Their mechanical behavior and long-term degradation directly govern the stability, serviceability, and resilience of geotechnical systems. The eight papers in this section examine their responses under coupled thermal, hydraulic, and mechanical conditions, with particular emphasis on freeze–thaw damage, fracture evolution, transport properties, and failure mechanisms.

Chen et al. [4] investigated the structural evolution of soil-ice composites and the dynamic mechanical properties of saline frozen soil subjected to freeze–thaw cycling. Using nuclear magnetic resonance, they proposed two T_2 cutoffs to distinguish bound,

https://doi.org/10.1016/j.ijmst.2026.09.007
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capillary, and bulk water, and clarified the mechanical contributions of different types of pore ice. They further developed a soil-ice co-evolution theory in which particle aggregation and fragmentation, pore-water transitions, pore interconversion, and changes in interparticle contacts collectively reshape the composite structure. Their decoupling analysis highlighted the dominant role of the ice skeleton in the dynamic response of saline frozen soil.

Huang et al. [5] examined the mechanical response and failure precursors of red sandstone under varying saturation and freeze–thaw conditions. Uniaxial compression tests, acoustic emission monitoring, and critical slowing down theory were combined to characterize strength degradation, crack evolution, and precursory behavior. The results showed that increased saturation and freeze–thaw damage intensified crack activity and reduced rock strength. Variations in the b-value, cumulative b-value, and critical slowing down indicators provided identifiable warning information before failure. The authors also proposed a conceptual framework linking initial damage, system recovery rate, and critical slowing down behavior.

Gao et al. [6] developed a fully coupled thermo-hydro-mechanical model for freeze–thaw damage in fractured rock. A discrete fracture network was adopted to represent the natural fracture system, while fracture initiation and propagation, ice-water phase change, thermo-poro-elastic response, and material-property degradation were incorporated into the model. After validation against laboratory experiments, the model reproduced nonlinear frost-heave deformation, the secondary peak of frost-heave pressure, and coupled matrix-fracture interactions. The simulations based on this model further showed that initial fracture-induced damage enhances storage and transport capacity, thereby promoting frost heave and progressive damage, while fracture network geometry controls the severity and spatial distribution of degradation.

Li et al. [7] proposed a unified micro–macro compression fracture model for unsaturated freezing brittle rocks. The model integrates a compression wing-crack framework, a fracture criterion, a crack-strain damage relation, and temperature- and saturation-dependent formulations for key mechanical parameters and crack-surface stresses. It enables the stress intensity factor, stress–strain response, crack initiation stress, and peak compressive strength to be evaluated within a unified framework. The authors identified a pore-structure-controlled three-stage mechanism involving skeleton-contraction strengthening, cohesive-stress strengthening, and frost-heave-induced offset. Comparisons with independent experimental data supported the applicability of the model to different rock types and saturation conditions.

Wang et al. [8] investigated the pore structure and permeability of slate subjected to freeze–thaw cycles at different immersion depths. Nuclear magnetic resonance, scanning electron microscopy, and permeability tests were used to characterize the development of internal damage. The results showed that freeze–thaw cycles increased both porosity and permeability, with more pronounced degradation under greater immersion depths. Moderate and full immersion conditions were particularly conducive to internal microcrack development. By incorporating the fractal dimension of the pore structure, the authors established a permeability model that accounts for initial porosity, freeze–thaw history, and immersion conditions, providing a quantitative basis for evaluating rock degradation and groundwater protection.

Zhang et al. [9] investigated freeze–thaw-induced fracture toughness degradation in granite under high-altitude cryospheric engineering conditions. A water-retaining Central Grooved Brazilian Disc specimen was designed to reproduce frost-heave effects in water-filled fractures. Mechanical testing, digital image correlation, and laser confocal microscopy revealed a two-stage degradation mechanism involving progressive microcracking followed by fatigue-induced spalling of intergranular material. To move beyond purely data-driven prediction, the authors developed a Physics-Informed Neural Network incorporating fracture-mechanics governing equations and boundary conditions. The resulting model provides a physically constrained approach for predicting the reduction in Mode-I fracture toughness.

Zhang et al. [10] examined crack evolution and the Kaiser effect in cold-region red sandstone subjected to freeze–thaw cycles and repeated loading. Constant-amplitude multi-stage cyclic loading tests were combined with nuclear magnetic resonance, acoustic emission monitoring, and Gaussian mixture model-based crack classification to relate macroscopic mechanical behavior to microcrack evolution. Freeze-thaw damage increased porosity, reduced P-wave velocity and fatigue strength, and altered the dominant fracture characteristics. The authors further established that the Kaiser effect corresponds to stable tensile crack propagation, whereas its transition to the Felicity effect is associated with frictional slip along shear cracks, providing quantifiable indicators for stability assessment and early warning.

Zhou et al. [11] investigated the dynamic mechanical response and fracture mechanisms of ice-filled jointed red sandstone under sub-zero temperatures. Modified split Hopkinson pressure bar tests showed that the dynamic compressive strength of rock-ice-rock composite specimens increased as temperature decreased. The ice layer influenced energy dissipation density, energy reflection coefficient, and load transfer, while lower temperatures promoted a transition toward axial splitting under dynamic loading. Scanning electron microscopy further revealed a shift from predominantly intergranular fracture to transgranular fracture. The authors also developed a theoretical stress wave propagation model incorporating unfrozen water films to interpret the observed temperature-dependent response.

3. Polar geotechnical hazards

Glaciers and rock slopes are among the most hazard-prone geotechnical systems in polar environments. Their instability is strongly influenced by fracture evolution, freeze–thaw processes, topographic conditions, and dynamic disturbance, posing serious risks to infrastructure and human activities. The two papers in this section address ice avalanche initiation and the dynamic instability of freeze–thaw-affected rock slopes.

Peng et al. [12] proposed a mechanics-based initiation criterion for ice avalanches by linking the rate- and temperature-dependent fracture behavior of ice to glacier-scale instability. Sentinel-2B imagery was used to characterize the pre-failure motion of the Sedongpu glacier and to establish a mechanical pathway in which glacier acceleration increases ice deformation rate, reduces fracture toughness, and promotes avalanche initiation. Low-temperature four-point bending tests further clarified the effects of strain rate and temperature on ice fracture toughness and crack-tip yield strength. By idealizing an unsupported ice mass as a crevassed cantilever beam, the authors identified overhang length and crack length as the principal geometric controls on tensile failure. The criterion was further examined using the Eiger hanging-glacier event, supporting the use of glacier acceleration as an observable indicator of progressive instability.

Deng et al. [13] investigated the dynamic response and failure evolution of a rock slope subjected to freeze–thaw cycles and seismic loading. Shaking-table tests, together with temperature-field measurements, Arias intensity, Fast Fourier transform, and Hilbert–Huang transform, were used to characterize slope damage from both time- and frequency-domain perspectives. The results showed that freeze–thaw cycles create a distinct interface on the slope surface, which promotes sliding initiation and alters

seismic-wave propagation through reflection, refraction, and transmission. The interface also causes amplification of high-frequency seismic energy in the overlying slope. Comparisons between freeze coagulation and thermal melting conditions revealed different sequences of deformation and failure, clarifying the role of the freeze–thaw interface in the dynamic instability of cold-region rock slopes.

4. Polar geotechnical technologies

Engineering activities in polar environments rely on technologies capable of operating reliably under low-temperature, ice-rich, and environmentally sensitive conditions. Their performance is essential not only to efficient exploration and engineering operations, but also to minimizing environmental disturbance. The three papers in this section present advances in submerged ice-breaking, replicate ice-coring, and hydrate-based carbon sequestration in permafrost regions.

Zhang et al. [14] proposed a viscoelastic submerged water jet to improve ice-breaking performance at long standoff distances. The study addressed the instability and rapid energy dissipation that limit conventional submerged water jets. The results showed that the polymer network in polyacrylamide solutions suppresses Kelvin–Helmholtz instability, raises the cavitation threshold, and concentrates flow energy into dominant low-order modes, thereby improving far-field jet stability. At a standoff distance of 45 times nozzle diameter, the viscoelastic jet increased the impact force by 175.3% and achieved an ice-cutting depth exceeding 80 mm, more than 3.6 times that produced by pure water. These improvements provide a promising technical route for efficient submerged ice-breaking in polar engineering operations.

Cao et al. [15] reviewed recent advances in sidewall-based replicate ice-coring technologies for ice-core research. They evaluated the working principles, performance, and limitations of field-proven replicate coring systems and the laboratory-validated Thermal Sidewall Ice Corer, and discussed the feasibility of transferring sidewall coring technologies from petroleum engineering to glacial environments. Based on this assessment, the authors proposed and experimentally validated the Sidewall Thermal Replicator and Sidewall Mechanical Replicator. Both systems can retrieve vertically aligned ice cores parallel to the main borehole axis without requiring borehole enlargement or auxiliary systems. Designed for standard borehole diameters, they are simple to operate and can substantially reduce nonproductive time.

Yang et al. [16] evaluated the carbon sequestration stability in ice lens covered permafrost and proposed a stability-enhancement strategy that utilizes naturally occurring ice phases. Their experiments showed that regenerated pore ice and ice lenses inhibit hydrate decomposition by restricting gas diffusion and regulating heat transfer. The ice-hydrate coupling effect prolonged sequestration duration by up to 231.9 min and increased the retained sequestration capacity by 31.8%. The authors further showed that the instability threshold is governed by asynchronous deformation between the ice and hydrate phases together with pore structure characteristics. These findings provide a pore-scale basis for improving the safety and long-term stability of hydrate-based carbon sequestration in permafrost regions.

5. Summary and outlook

This Special Issue presents recent advances in polar geotechnical engineering and environmental protection. The contributions improve the understanding of polar geomaterials and cryospheric geohazards while introducing new technologies for engineering operations and environmental management. The studies reveal how low temperature and freeze–thaw processes influence the structure and mechanical behavior of frozen soils and cold-region rocks. They also advance the assessment of ice avalanches and freeze–thaw-affected rock slopes. Further progress is demonstrated in submerged ice-breaking, replicate ice-core sampling, and hydrate-based carbon sequestration. These contributions collectively provide theoretical and technological support for safer and more sustainable engineering in the Arctic, Antarctic, the Third Pole and other polar-like cold regions.

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