frontiers | Frontiers in Built Environment

TYPE Editorial
PUBLISHED 08 October 2025
DOI 10.3389/fbuil.2025.1701182

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OPEN ACCESS

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RECEIVED 08 September 2025
ACCEPTED 22 September 2025
PUBLISHED 08 October 2025

CITATION
Wu J, Chen W, Shi H, Ma D and Wong HS (2025) Editorial: Advanced materials and technologies for sustainable development of underground resources.
Front. Built Environ. 11:1701182.
doi: 10.3389/fbuil.2025.1701182

Editorial: Advanced materials and technologies for sustainable development of underground resources

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KEYWORDS

advanced materials, advanced technologies, sustainable development, underground resources, geotechnical engineering

Editorial on the Research Topic
Advanced materials and technologies for sustainable development of underground resources

The sustainable development of underground resources faces mounting challenges from extreme mining conditions—such as high stress, high temperature, and high groundwater pressure—as well as significant environmental impacts caused by mining waste. This Research Topic presents cutting-edge advances in material innovation and engineering technology aimed at enabling safe, green, and efficient resource extraction. Featured contributions span microstructure characterization and performance enhancement of backfill and grouting materials, investigations into rock mechanics under multi-field coupling conditions, stability monitoring and disaster prediction based on multi-source information, support technologies for deep roadways under high disturbance, and microscopic and numerical studies of material degradation mechanisms. This Research Topic provides theoretical insights and practical solutions that promote the sustainable exploitation of underground resources through interdisciplinary integration across geotechnical engineering, materials science, and environmental technology, thereby advancing innovative development in the field.

Understanding the mechanical properties of geotechnical materials is fundamental to all geotechnical engineering activities and decision-making. However, as engineering activities extend deeper into the Earth, the complex deep geological environment significantly alters these mechanical characteristics. Therefore, investigating the mechanical response, failure mechanisms, and constitutive relationships of geotechnical materials under such conditions using advanced methods is crucial for advancing deep engineering projects. Zeng et al. found that freeze-thaw cycles markedly reduce rock strength and elastic modulus, and promote a shift in internal cracks from tensile to shear types. Damage severity was observed to escalate under intensified freeze-thaw conditions. Through systematic experiments, Li et al. revealed how scale effects influence particle breakage in coarse-grained soils. They reported that with a fixed maximum particle size, breakage decreases logarithmically as gradation area expands, whereas with a constant gradation area, breakage increases exponentially with larger maximum particle size. Their scale effect prediction model offers an effective tool for accurately forecasting particle breakage in structures such as earth-rock dams. Fu et al. used indentation tests under triaxial stress and observed that confining pressure significantly affects the breakage behavior of green sandstone. Under high axial pressure, breakage load and energy consumption first decrease then increase with rising confining pressure, while the opposite trend occurs under low axial pressure. They identified the reduced total number of cracks under high axial pressure as the main reason for lower energy consumption. Li et al. explored the scale effects of maximum particle size and gradation area on shear strength parameters of coarse-grained soils. They developed a correction model that provides a new method for accurate shear strength prediction in practical engineering. Cao et al. analyzed the mechanical properties of concrete-high water content material composites (CHWC) through uniaxial compression tests. Their work offers a theoretical basis for applying soft-top rigid-bottom filling technology in gob-side entry retention support. Gong et al. employed one-dimensional consolidation tests to examine the compression deformation behavior of soil-rock mixtures. Their results demonstrate the dominant role of fine-grained soil properties in long-term settlement and provide key insights for deformation prediction in geotechnical engineering. Wang et al. addressed the hazard of dolomite sandification in the Central Yunnan Water Diversion Project by establishing a four-grade classification standard, revealing that higher degrees of sandification lead to more developed pores and lower strength. Liu et al. studied the dynamic mechanical properties of concrete under sulfate attack. They revealed the relationship between sulfate erosion and strain rate sensitivity, which supports the design of impact-resistant concrete in corrosive environments. Ma et al. discovered that rocks with lower peak strength exhibit higher fractal dimensions in fragments and more fully developed cracks in failure zones. In contrast, Lou et al. reported that as the horizontal distance between holes and fractures increases, the bearing capacity and deformation resistance of rock samples decline. They also observed failure modes shifting from tensile-shear mixed to tensile-dominant and internal crack propagation simplifying from exterior to interior. Mao et al. observed that in coal-bearing sandstone subjected to freeze-thaw cycles, wave velocity decreases and porosity increases as freezing temperature drops and cycle number rises. This process is accompanied by significant expansion in pore number and size. Jiang et al. established a correlation model between wave velocity and permeability of sandstone at high temperatures. They proposed a new method for monitoring surrounding rock stability in high-temperature fluidized mining. Feng et al. developed a constitutive model based on the Duncan-Chang framework that effectively represents the mechanical behavior of frozen calcareous clay under multi-factor coupling. Hu et al. investigated how bedding angles influence tensile failure of coal rock through Brazilian splitting tests and numerical simulation. They created a continuous-discrete numerical model that effectively predicts fracture behavior in stratified coal rock and supplies key parameters for similar projects. Zhang et al. studied damage patterns in sandstone under two types of cyclic loading and proposed a three-stage damage evolution model for loaded rock. They noted that acoustic emission responses remain synchronized with stress after low-frequency cyclic static loading. Yin et al. used laboratory model tests to analyze spatial temperature field distributions in road-bridge transition sections in permafrost regions. Their results show that the influence of atmospheric temperature changes weakens and lags noticeably with increasing depth below the subgrade surface.

Stress, seepage, temperature, and chemical interactions are all critical factors governing the mechanical behavior and stability of geotechnical materials. In practical engineering, however, the coupling of multiple physical fields creates a complex environment that promotes the initiation and evolution of disasters. Research indicates that multiphysics coupling mechanisms profoundly affect the long-term safety of geotechnical structures and disaster formation. For instance, Yang and Chen uncovered the disaster-induced mechanism of precipitation-induced foundation pit deformation through seepage-stress coupling, highlighting its role as a major triggering factor. Kong et al. revealed the plastic failure mechanism of a coal seam floor under coupled mining-induced stress and water pressure. Gong et al. elucidated the time-dependent deformation behavior of fault rock under axial pressure, confining pressure, and water pressure using a stress-seepage-time coupling model. Guo et al. demonstrated that controlling material density can effectively suppress seepage-related disasters. In the area of thermal-mechanical coupling, Yin et al. and Shi et al. proposed methods for preventing frost damage in cold-region tunnels based on geothermal field optimization and frost heave mechanisms, respectively. Tao et al. and Sun et al. further revealed, at the meso-level, the influence of freeze-thaw and loading coupling on rock damage and energy evolution mechanisms. Additionally, Liu et al. emphasized the importance of interface effects in the stability of high-level radioactive waste repositories under seepage-stress-chemical coupling conditions. These studies systematically advance the theoretical understanding from single-field to multi-field coupling, providing a critical scientific basis for geotechnical disaster prevention and control.

Currently, traditional support materials often prove inadequate in addressing complex deep underground conditions, such as high *in situ* stress and strong mining-induced disturbances. There is an urgent need to comprehensively enhance their strength, toughness, and functionality through research on new support structures, modification mechanisms of grouting and backfill materials, mechanical properties, and engineering application effectiveness. Yu et al. investigated the energy dissipation mechanism of gangue specimens with varying particle size distributions under compression and identified interparticle friction as the dominant factor governing energy dissipation. Their findings provide a theoretical basis for the selection and gradation optimization of backfill materials. Song et al. studied a novel segmental cemented honeycomb structure and explored its mechanical properties and energy absorption characteristics for supporting large-deformation roadways. Their results confirm the structure's applicability under dynamic disaster conditions. Zhang et al. proposed an integrated "yield-bolt-grouting" coupling control technology system based on laboratory experiments. Field monitoring and engineering practice verified that this technology effectively controls surrounding rock deformation. Shen et al. established a linear relationship between micro-crack length and splitting tensile strength, demonstrating that interlayer treatment significantly enhances interfacial performance. Gao et al. were the first to highlight the critical role of the soil arching effect ahead of the anchor head in pull-out resistance. Their work provides important meso-mechanical insights and numerical simulation references for the optimal design of belled anchors in anti-floating and foundation pit support projects. Li et al. used numerical simulations to confirm that the incorporation of carbon nanotubes (CNTs) markedly improves the compressive strength and deformability of grouting materials, with results showing high consistency with experimental data. Luan et al. developed an optimized predictive model for the performance of ultra-high performance concrete with coarse aggregate (UHPC-CA) through comparative analysis, providing a basis for its application in marine structures. (Ling and Ying) systematically analyzed the displacement and stress distribution characteristics of roadway surrounding rock using a combination of FLAC3D numerical simulations and field measurements. Based on conditions in the 11th mining area of Yindonggou Coal Mine, Li et al. introduced a "differentiated support" concept founded on differences in surrounding rock lithology and structural stress. Field applications demonstrated that this approach effectively controls surrounding rock deformation.

With the continuous expansion of mine construction scales, the movement, deformation, and failure of overlying strata induced by mining activities have become increasingly severe. The field of underground engineering urgently needs to break through the limitations of traditional monitoring technologies and develop a real-time stability monitoring system based on multi-source information fusion. This will enable proactive perception and intelligent regulation of engineering safety conditions. Du et al. employed a probability density function method to fit surface subsidence under insufficient mining conditions and achieved higher accuracy compared to traditional methods. Their zonal inversion strategy significantly improved fitting accuracy at the basin edges, offering a new approach for subsidence prediction. Wang et al. utilized a full-fiber microseismic system to analyze rock pressure behavior and identified a positive correlation between microseismic activity and advance speed, along with precursory characteristics of microseismic events. Ma et al. investigated the large deformation mechanism of roadways under fault influences and found that deformation on the fault-proximal side increased by 140%. Through simulations and field measurements, Xu et al. revealed the asymmetric instability characteristics of surrounding rock under dynamic loading and the corresponding response of rock bolts, validating the effectiveness of their model. Li et al. conducted multi-scale simulations to study the failure processes of shallow buried weakly cemented overlying strata and elucidated the evolution law of water-conducting fractures. Zhang et al. used physical experiments and DIC technology to uncover the fracture and energy release mechanisms of surrounding rock in deep roadways under dynamic loading, providing a basis for dynamic disaster prevention and control. From a mesoscopic perspective, Hu et al. studied the fracture behavior of jointed roadways and revealed the mechanism by which bolt restrains tensile failure, as well as the negative correlation between joint density and stability. Zhu et al. integrated multiple methods to investigate the control mechanism of tectonic stress on key stratum breaking and the formation of "plate-shell" structures, validating the theory through practical application and providing a basis for rock pressure control. Zhang et al. applied acoustic emission and DIC technology to study fracture modes in fractured rock masses and found that normalized global strain curves can effectively identify damage patterns. Tian et al. introduced an EMD-SSA method for processing electromagnetic ultrasonic signals, which significantly improved the accuracy of pipeline inner wall corrosion detection and provided a reliable nondestructive testing technology. Through field measurements and simulations, Zhou et al. proposed a "fan-shaped seesaw" structural model that explains the mechanism of strong rock pressure. They also used hydraulic fracturing technology to effectively control the roof, offering important technical support for ground control.

Deep mining faces extreme conditions such as high ground pressure, high temperatures/freeze-thaw cycles, fault activation, mineral mineralization, and groundwater environments, making it significantly different from shallow resource extraction. Therefore, understanding the response mechanisms of resource development in deep environments is of great importance. Liu et al. employed micro-CT and FIB-SEM techniques to characterize the microstructure of tight reservoirs and developed a permeability prediction model. Their study revealed that micrometer-scale throats dominate fluid flow, providing critical support for efficient reservoir development. Based on a case study of Guojiawan Coal Mine, Wu et al. integrated rock testing and 3DEC simulations to optimize hydraulic fracturing design. Field tests demonstrated the most effective fracturing outcomes in the central goaf area, resulting in a mature roof control technology system. Qin et al. investigated surrounding rock deformation during ultra-thick coal seam mining and proposed a trapezoidal block structure instability model. They elucidated the mechanisms of slip and rotational instability, which were subsequently validated through engineering applications. Gong et al. analyzed deep karst water chemistry in the Huaibei Plain and identified evaporite dissolution and silicate weathering as the primary processes governing hydrogeochemical characteristics, offering a scientific basis for groundwater exploitation and water-in rush prevention. Liu et al. conducted studies on the Qingchengzi mining cluster and confirmed that the Shuangdinggou and Xinling granitic bodies are co-genetic and deeply interconnected, collectively controlling the distribution of Pb-Zn ore deposits. Shi et al. established a failure model for water inrush mechanisms at the working face of shallow-buried sand layer tunnels using numerical simulations and theoretical analysis. They derived an exact analytical solution clarifying the influence of multiple parameters on tunnel stability.

Author contributions

JW: Writing – original draft. WC: Writing – original draft. HS: Writing – review and editing. DM: Writing – original draft. HW: Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We would like to express our heartfelt gratitude to all the authors who contributed to this Research Topic, and to the dedicated editorial team for their exceptional efforts and unwavering support in bringing this Research Topic to publication.

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