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Editorial

Effects of Temperature on Geotechnical Engineering

Jiliang Pan

School of Resources and Safety Engineering, University of Science and Technology Beijing, Beijing 100083, China; panjiliang@ustb.edu.cn

1. Introduction

Temperature is a fundamental environmental and engineering variable in geotechnical problems. Its influence is reflected not only in the strength, stiffness, deformation, permeability, and durability of rocks and soils, but also in the long-term stability and serviceability of geotechnical engineering structures. With the expansion of human engineering activities into cold polar regions, high-altitude permafrost areas, deep hot rock formations, and even extreme environments associated with extraterrestrial construction, geotechnical engineering is increasingly exposed to complex and severe temperature conditions. In addition, emerging engineering fields, such as geological energy storage, geothermal resource development, natural gas hydrate extraction, and the geological disposal of high-level radioactive waste, have created new challenges related to temperature-induced material degradation, multi-field coupling, and long-term safety.

Temperature affects geotechnical engineering in two distinct but closely related ways. On the one hand, it acts as a passive environmental factor. Under low-temperature conditions, freeze–thaw cycles can cause frost heave, thaw settlement, pore-water phase transition, crack propagation, and progressive degradation of frozen soils and rocks [1,2]. Under high-temperature conditions, thermal expansion mismatch among mineral grains, thermal stress accumulation, and thermally induced cracking may significantly alter rock strength, deformation, and permeability [3,4]. In cyclic thermal environments, repeated temperature fluctuations may lead to fatigue damage, deterioration of mechanical properties, and changes in failure mode [5]. In deep underground engineering, temperature rarely acts alone; instead, it interacts with in situ stress, groundwater seepage, chemical environment, and excavation disturbance, forming complex thermo–hydro–mechanical (THM) or thermo–hydro–mechanical–chemical (THMC) coupling processes [6].

On the other hand, temperature can also serve as a controllable engineering factor for improving stratum stability, assisting mechanical rock breaking, optimizing thermal recovery performance, or assessing the influence range of thermal disturbance. Artificial ground freezing is a representative example, in which low temperature is deliberately used to convert water-bearing soft ground into a temporary frozen structure with improved strength, stiffness, and water-tightness [7,8]. This method is widely used in tunnel construction, shaft excavation, connecting-channel construction, and underground space development under difficult hydrogeological conditions. Similarly, high temperature or controlled temperature gradients may be used to assist rock breaking by inducing thermal stress, weakening mineral bonding, promoting crack initiation, and reducing mechanical cutting or drilling resistance [9,10]. Such temperature-assisted rock breaking has potential significance for deep mining, geothermal reservoir stimulation, hard-rock excavation, and planetary subsurface exploration.

This Special Issue was organized to present recent advances in understanding and exploring the influence of temperature on geological materials and geotechnical sys-

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tems. The published papers cover freeze–thaw damage, high-temperature rock mechanics, temperature-confining pressure coupling, periodic thermal fatigue, temperature-dependent soil creep, artificial freezing construction, deep reservoir fracturing, geothermal system optimization, and THM coupling behavior in high-geothermal tunnels. From the perspectives of material testing, theoretical modeling, numerical simulation, and engineering application, these papers demonstrate the complexity and diversity of temperature effects in geotechnical engineering. Together, these studies provide valuable experimental data, theoretical models, numerical methods, and engineering insights for advancing this important field.

2. An Overview of Published Articles

2.1. Freeze–Thaw Deterioration

Li et al. (contribution 1) investigated the constitutive characteristics of rock damage under freeze–thaw cycles. By introducing a cumulative damage variable associated with the number of freeze–thaw cycles and assuming that rock strength follows a Weibull distribution, they established a cumulative damage constitutive model for rock shear strength attenuation based on the Mohr–Coulomb criterion. The proposed model can describe the mechanical behavior of rocks under different confining pressures and freeze–thaw cycles, including strain softening and residual strength characteristics. This work provides a useful theoretical framework for evaluating freeze–thaw-induced deterioration in cold-region rock engineering.

Yang et al. (contribution 2) examined the mechanical properties of rubber fiber-reinforced expansive clay subjected to freeze–thaw cycles. Their triaxial test results showed that adding rubber fibers from waste tires significantly reduces the adverse effects of freeze–thaw cycles on shear strength and elastic modulus. In contrast to unreinforced expansive clay, whose strength and stiffness decrease markedly with increasing freeze–thaw cycles, the reinforced clay exhibited only slight deterioration. This study not only contributes to the improvement of expansive soils in seasonal frozen regions but also provides a sustainable approach for recycling waste tires in geotechnical engineering.

2.2. High-Temperature Mechanical Behavior

Qin et al. (contribution 3) studied the physical and mechanical properties of granite after high-temperature treatment while considering anisotropy. Through wave velocity tests, microscopic observations, and uniaxial and triaxial compression tests on samples taken from three orthogonal directions, they showed that high temperature changes the density and orientation of thermal cracks in granite. Temperatures below 400 °C increased the anisotropy of granite, while more severe thermal damage occurred at higher temperatures. The study further showed that samples taken parallel to the dominant crack direction exhibited better mechanical properties under the same temperature condition. These findings are important for dry hot rock exploitation, nuclear waste disposal, and deep rock engineering where granite is often used as a key host or reservoir rock.

Zheng et al. (contribution 4) investigated the deformation and failure characteristics of four rock types—granite, red sandstone, gray sandstone, and shale—under coupled temperature and confining pressure. Their results indicated that high temperature causes internal structural damage and crack propagation, reducing compressive strength and elastic modulus, whereas high confining pressure can inhibit crack propagation and improve rock deformation capacity. They also found that different rock types exhibit distinct failure modes under thermo-confining pressure coupling. Based on the experimental results, they modified the Drucker–Prager criterion parameters and developed a damage constitutive

model that can represent the stress–strain behavior of rocks under coupled temperature and pressure conditions.

2.3. Cyclic and Time-Dependent Thermal Effects

Guo et al. (contribution 5) investigated the influence of periodic temperature on acoustic emission, strength, and deformation characteristics of salt rock. Motivated by the cyclic injection and withdrawal processes in salt cavern gas storage, they performed uniaxial compression tests on salt rock samples after thermal fatigue treatment and combined acoustic emission monitoring with digital image correlation. Their results showed that increasing the number of cycles and the upper temperature limit promotes microcrack propagation, structural damage accumulation, radial deformation, and local displacement concentration. After 40 cycles, the compressive strength and elastic modulus decreased by 23.8% and 27.4%, respectively, and the failure mode gradually shifted from tension-dominated to tension–shear composite. This study provides important support for evaluating the long-term safety of underground salt cavern storage.

Xu et al. (contribution 6) analyzed the creep characteristics of dredged fill soil from Humen Port under different temperatures. Through triaxial creep tests under drained and undrained conditions, they showed that increasing temperature significantly accelerates creep deformation. The dredged fill soil was characterized by high water content, large void ratio, high compressibility, low shear strength, and low permeability, making its long-term settlement behavior highly sensitive to temperature. Based on the experimental results, they developed a Burgers-type creep constitutive model considering temperature effects, providing a useful tool for long-term stability assessment and settlement prediction of reclaimed foundations in coastal environments.

2.4. Numerical Methods and Engineering Insights

Zhang et al. (contribution 7) studied the deformation of adjacent pipelines caused by connecting-channel excavation reinforced with the freezing method. By combining field measurements, numerical simulation, and theoretical analysis based on Euler–Bernoulli beam theory, they evaluated the effects of freezing temperature and excavation parameters on pipeline settlement. Their results showed that excavation rate strongly affects pipeline deformation: when the excavation rate exceeds 1.0 m/d, settlement increases rapidly. Lower freezing temperatures can form thicker and stronger frozen soil walls, thereby enhancing support capacity and reducing ground disturbance. This paper highlights the active role of temperature control in underground construction safety.

Li et al. (contribution 8) developed a three-dimensional finite–discrete element model (FDEM) to simulate multi-cluster hydraulic fracturing under the influence of natural fractures. Their results demonstrated that increasing the number of fracturing clusters and natural fractures generally enlarges the total artificial fracture area and promotes more complex fracture networks. The presence of natural fractures can also alter artificial fracture propagation paths and failure modes, producing phenomena such as single-wing propagation, bifurcation, and fracture bending. Although the study focuses on deep shale reservoirs, its findings are also relevant to geothermal reservoir stimulation and deep energy engineering, where fracture-network geometry strongly controls fluid flow and heat extraction.

Liu et al. (contribution 9) proposed an adaptive Kriging-based optimization method for heat production performance in a two-horizontal-well geothermal system. To reduce the high computational cost of numerical simulations, they combined computer simulation with Kriging approximation and developed a parameterized lower confidence bounding sampling scheme to update the surrogate model adaptively. Their optimization framework

considered fracture spacing, injection flow rate, and well spacing, with total power generation as the objective. The study provides an efficient computational strategy for geothermal system design and performance evaluation.

Wu et al. (contribution 10) studied the evolution of the thermal influence zone in high-geothermal tunnels under THM coupling. Unlike many conventional models that assume a uniform initial temperature field, their model incorporated an in situ geothermal gradient and quantitatively defined the thermal influence zone using an equivalent-radius method. The results showed that the thermal influence zone expands nonlinearly with increasing initial rock temperature and gradually stabilizes over time. Temperature and pore water pressure both promote plastic-zone development, but temperature plays the dominant role under the studied conditions by inducing thermal stress and degrading mechanical properties. This work provides quantitative guidance for support design and stability control in high-geothermal tunnels.

3. Conclusions

The papers in this Special Issue advance the field by deepening mechanistic understanding of temperature-induced damage, reinforcement, creep, anisotropy, and coupled deformation in geological materials; developing constitutive and numerical models for temperature-dependent behavior under realistic stress, drainage, and engineering conditions; and linking laboratory observations with field-scale problems such as frozen-ground construction, high-geothermal tunnels, geothermal energy extraction, salt cavern storage, reclaimed foundations, and deep reservoir stimulation.

Collectively, these studies show that temperature effects in geotechnical engineering are multi-scale, multi-process, and strongly coupled. At the material scale, freeze–thaw cycles, high-temperature treatment, cyclic thermal loading, and temperature-dependent creep can significantly alter the pore structure, crack development, wave velocity, strength, stiffness, deformation behavior, and failure mode of rocks and soils. At the modeling scale, temperature-dependent damage models, creep models, surrogate optimization methods, and THM coupling numerical models provide increasingly powerful tools for describing and predicting complex geotechnical responses. At the engineering scale, the published studies show that temperature is not only a source of deterioration and risk but also a controllable variable in artificial freezing, geothermal energy extraction, and tunnel thermal disturbance management. Overall, this Special Issue highlights the importance of temperature as a central variable in modern geotechnical engineering and provides a foundation for future studies on safer, more durable, and more sustainable geotechnical systems under complex environments.

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