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Editorial

Thermal-Hydraulic-Mechanical (THM) Coupling Behaviour of Fractured Rock Masses

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Fractured rock masses are rich in defects of different scales, including pores, microfractures, joints/fractures, and macroscopic discontinuities; the presence of these defects changes the mechanical properties of the rock masses to some extent (deformation modulus and strength parameters are reduced, and the rock masses are anisotropic) and also affects the permeability characteristics of the rock masses [1–3]. Along with the increased exploitation of underground space, the geological environment in which the deep rocks are located is special, presenting mechanical characteristics such as high in situ stress, high ground temperature, and high karst water pressure. Regardless of deep oil and gas exploits, geothermal energy, high dams for water and hydropower, tunnels, nuclear waste disposal and mining projects, etc., the interactions of human engineering interference forces, rock in situ stress, and groundwater permeability during excavation of these underground projects induce redistribution of the stress field, which induces damage and evolves into macroscopic fractures [4]. The damage will result in a dramatic change in the permeability of the rock mass, changing the seepage field in the rock mass, and the fracture permeability intensifies the fracture initiation, prolongation, and coalescence of rock fractures [5], initiating water inrush and leading to progressive unstable failure of the rock mass [6]. Further, this process is also the process of seepage leading to the deterioration of rock strength damage and the change of surrounding rock stress field. The change of rock stress and the expansion of rock fracture damage lead to the change of fractured rock permeability characteristics, which will change the distribution of the seepage field. For instance, when the top and bottom of the roadway the surrounding rock is sudden damage, high water pressure karst water because of the relative concentration of water gushing channel and cause serious water inrush disaster [7]. Due to mining and other disturbances, the destruction of rock mass is aggravated, and the water inrush disaster has obvious characteristics of instantaneous suddenness and unpredictability. The existing literature shows that the brittle failure caused by crack propagation and coalescence of adjacent joints under geological environment and engineering disturbance is a typical failure mode of the engineering rock mass. Extensive engineering practice shows that the existence and change of seepage fields are one of the important reasons for the instability of fractured rock mass engineering and even large-scale geological disasters. The problem of THM field coupling interaction during fracture rock fracture process has already become a current research hot spot in rock engineering; therefore, the study of THM coupling behaviour is of great significance in geological rock engineering.

Laboratory tests show that the coupling between rock stress, fluid flow, and temperature is closely related to the geometric shape, fluid characteristics, and stress and temperature conditions of the fracture network. Recently, using multiple methods such as laboratory experiments, theoretical analysis, and numerical simulation, fluid flow in fractured rock masses under various stress and temperature conditions is studied. However, due to the extremely complex occurrence environment of rocks and rocks, because it involves the comprehensive influence of load, geometric shape, and stress environment, the comprehensive insight into the THM coupling process is often hindered. Therefore, the study of mechanical properties and permeability of fractured rock mass, nonlinear flow in fracture, and new experimental and numerical methods is actually quite a challenging topic.

Over the past decades, a great number of pioneering and fruitful researches have been conducted on "THM behaviour of fractured rock masses" in physical tests [8], numerical simulations [9, 10], and theoretical studies, and a wealth of research results and research experiences have been accumulated, while experimental studies are the most commonly used. Following the rapid development of computer science, numerical methods are gradually and widely used in rock (soil) engineering, becoming an effective tool esteemed by rock (soil) workers to effectively establish and process complex virtual models closer to the real world, creating more reliable results for geotechnical engineering design and evaluation. Here, several numerical methods are proposed to simulate the coupled THM effects of fractured rock masses, and the majority of the simulation results show good agreement with experimental results. In this special issue, a series of research papers on rock masses or rock-like materials are presented. The effects of environmental impact, loading conditions, and dimensional effects on the structural deterioration of rock masses, such as the coupling effect of seepage and stress fields, acidification, freeze-thaw cycles, and mechanical behaviour of rock masses by dry and wet cycles, were evaluated. Besides, the issue discusses new methods used to characterize the THM behaviour of rocks.

The coupling effect of THM fields significantly affects the mechanical behaviour of the rock mass. In most engineering cases, such as roadway excavation, rock slope, and pillars in deep mining activities, they are often eroded by groundwater. Therefore, it is necessary to estimate the strength and failure characteristics of water-bearing fractured rock mass [11–14]. In this special issue, the impact of coupled THM field interaction effects on the mechanical behaviour of rock masses in terms of failure mechanisms is described: "Study on the Damage Evolution Process and Fractal of Quartz-Filled Shale under Thermal-Mechanical Coupling" by Z. Wu et al., "Destruction Law of Borehole Surrounding Rock of Granite under Thermo-Hydro-Mechanical Coupling" by J. Wu et al., "A Study of the Solid-Liquid-Gas Three-Phase Coupling Relationship of Coal, Water and Gas" by A. Yuan et al., "Experimental Study on Permeability Coefficient in Layered Fine Tailings under Seepage Condition" by T. Dong et al., and "Thermos-Solid-Gas Coupling Dynamic Model and Numerical Simulation of Coal Containing Gas" by X. Fukun et al. In the above articles, the effect of the coupled hydraulic-mechanical field effect on the damage of the rock is considered. In addition, in order to study the damage behaviour of rock masses under different stress environments, scholars performed a series of experimental or numerical studies, and the effect of loading conditions on the mechanical behaviour of rock masses was analyzed in the paper: "Experimental Studies on Cracking and Local Strain Behaviors of Rock-Like Materials with a Single Hole before and after Reinforcement under Biaxial Compression," "Study on the Damage Model of Coal Rock Caused by Hydraulic Pressure and Electrical Impulse in Borehole," "Triaxial Creep Behavior of Red Sandstone in Freeze-Thaw Environments," and "Fracture Failure Characteristics of Jointed Sandstone under Uniaxial Compression."

The mechanical behaviour of rock masses is influenced by the coupling effects of THM fields, as well as by the geological environmental conditions. The failure characteristics of fractured rock masses can be very different compared to those under natural conditions as environmental factors change (such as acidification, freezing-thawing cycles, and dry and wet cycles). Environmental factors were also taken into account in this issue. For instance, W. Chen et al. carried out a series of uniaxial acidified creep tests and studied the influence of acidified environment on rock damage and established a creep model. The results show that the stronger the acidity, the greater the rock damage (see their papers for details: "Features and Constitutive Model of Gypsum's Uniaxial Creep Damage considering Acidization"). The damage statistical empirical model for fractured rock under the freezing-thawing cycle and loading are presented. For instance, Y. Chen et al. establish the freezing-thawing constitutive relationship of fracture rocks from the perspective of damage statistics ("Damage Statistical Empirical Model for Fractured Rock under Freezing-Thawing Cycle and Loading"). As the results show, the obtained statistical empirical constitutive curves of damage to fractured rocks after a specific freezing-thawing cycle agree well with the experimental results, verifying the validity of the established constitutive relationships. In the paper "Experimental Study on the Damage and Degradation Characteristics of Red Sandstone after Dry and Wet Cycling by Low Magnetic Field Nuclear Magnetic Resonance (NMR) Technique," Y. Zhao et al. tested red sandstone after dry and wet cycling at different times using the NMR technique. The result shows that the degree of damage to the rock increases with the number of wet and dry cycles and eventually tends to be constant.

Recently, following the development of laboratory testing techniques, new techniques and methods have been increasingly applied to the study of the THM coupling behaviour of fractured rock masses. Then, testing techniques are also emphasized in this issue. In the paper "Study on the Microscopic Fracture Process and Acoustic Emission of Shale Based on Digital Image," M. Tang et al. studied on damage evolution of rocks using acoustic emission technique, and the results showed that the characteristics of the AE activity cycle were classified into two styles, surge style and step style, where the surge style had a short active period, a small number of AE counts with surges, a large AE peak, and a relatively simple damage pattern. The step style has a long activity cycle, a sharp increase in AE counts, a small AE peak, and a relatively complex damage pattern. In the paper "Rock Fracture Monitoring Based on High-Precision Microseismic Event Location Using 3D Multiscale Waveform Inversion," Y. Wang et al. introduce a rapidly evolving waveform inversion localization method to the mine MS site by modeling the wavefield using a high-resolution 3D velocity model, a fractional-order Gaussian wave source time function, and spectral element method (SEM) wavefield modeling. The results show that the multi-scale waveform inversion method can obtain similar localization accuracy as the waveform inversion based on a single fine grid, which can significantly reduce the iteration time and the computational cost of wavefield modeling. In the paper "Prediction of Stope Stability Using Variable Weight and Unascertained Measurement Technique," Q. Kang et al. proposed a new method to analyze the stability, practicality, and effectiveness of mining accidents.

Numerical simulations are an economical and practical method to simulate the coupled THM processes in rock masses compared with in situ and laboratory tests. Overall, the majority of numerical simulation results show excellent agreement with experimental results. In this special issue, several numerical methods are also discussed. Damage behaviour of coal rocks coupled by hydraulic pressure and electrical impulse in borehole was simulated. X. Bao et al. (in their paper "Study on the Damage Model of Coal Rock Caused by Hydraulic Pressure and Electrical Impulse in Borehole") used ABAQUS/XFEM to simulate the damage behaviour of coal rocks coupled with hydrostatic pressure and electrical impulse loading electrohydrogen and verified the damage variables and constitutive model by the damage and deformation characteristics of coal rock groups under different loads. The feasibility and correctness of the damage variables and constitutive models were verified by the damage and deformation characteristics of coal rock populations under different loads. X. Bao et al. (in their paper "Study on the Damage Model of Coal Rock Caused by Hydraulic Pressure and Electrical Impulse in Borehole") used PFC2D to simulate the three-point bending fracture toughness behaviour of conglomerate semicircular specimens, revealing that the peak load fluctuation during fracture extension is due to the continuous infiltration or influx of gravel particles from the fracture. Y. Pan et al. (in their paper "Coupled Hydraulic-Thermal Modelling and Related Numerical Analysis on Rock Fractures") simulated the fluid-thermal coupling effect of discontinuous rock masses using FRHT3D. Significantly, in this issue, besides the numerical methods mentioned above, other methods developed by authors were used to simulate the coupled THM damage processes in rocks or rock-like materials. In addition, engineering cases related to THM coupling are also presented in "Karst Aquifer Water Inflow into Tunnels: An Analytical Solution," "Grouting Treatment of Water and Mud Inrush in Fully Weathered Granite Tunnel: A Case Study," and "Surrounding Rock Failure Characteristics and Water Inrush Mechanism of Roadway above the Aquifer in Nonuniform Stress Field."

The factors influencing coupled THM behaviour of fractured rock masses include but are not limited to the above aspects. In addition, new experimental test techniques or numerical methods for the understanding of the coupled THM behaviour of fractured rock masses are still not listed all here one by one. There are also many excavations that face the problem of rock crack extension and softening mechanics behaviour when water is encountered, especially in deep mining. For deep mining, the in situ stress increases with increasing mining depth, while the geological environment becomes more complex. Then, the mechanical behaviour of the rock mass becomes more complex and unpredictable for water exposure and high temperature leading to crack propagation and softening. Hence, there are more unknowns in this field waiting to be explored and discovered in the future.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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