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Ph.D. DISSERTATION DEFENSE

Candidate: Yuntian Teng
Degree: Doctor of Philosophy
School/Department: Charles V. Schaefer, Jr. School of Engineering and Science / Department of Civil, Environmental, and Ocean Engineering.
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Title: Non-Darcian Flow, Multiphase Flow, and Hydration Thermodynamics in Subsurface Energy and Environmental Systems

Chairperson: Dr. Cheng Chen, Department of Civil, Environmental, and Ocean Engineering, School of Engineering & Sciences

Committee Members: Dr. Yi Bao, Department of Civil, Environmental, and Ocean Engineering, School of Engineering & Sciences, Stevens Institute of Technology
Dr. George Korfiatis, Department of Civil, Environmental, and Ocean Engineering, School of Engineering & Sciences, Stevens Institute of Technology
Dr. Rui Qiao, Department of Mechanical Engineering, College of Engineering, Virginia Tech

ABSTRACT

Nuclear energy contributes to 18% of national electricity generation. However, spent fuel is currently stored on the surface, necessitating constant monitoring, which incurs significant costs. After decades of research, long-term geological storage of high-level nuclear waste has become a consensus, requiring permanent sealing with engineered clay barriers. Clay is a buffer and backfill material in geological repositories for high-level nuclear waste due to its high swelling pressure, naturally low permeability and porosity, and strong solid-liquid interactions between water and smectite mineral surfaces. Furthermore, high-level nuclear wastes continue releasing heat for centuries, leading to complex water flow conditions and cycles of local hydration and dehydration in the engineered clay barrier.

In this dissertation, we first developed novel core-flooding equipment to reveal the relationship between the threshold pressure gradient and permeability under various temperatures in a clay-sand mixture, validating the two-parameter continuum-scale model to predict both non-Darcian and Darcy flow regimes. Second, we conducted a comprehensive review of non-Darcian flows in low-permeability porous media by compiling existing experimental data and comparing current models. Next, we utilized cyclic hydration gravimetry and calorimetry methods to uncover the mechanism of hydration hysteresis in swelling smectites, which is driven by phase transitions controlled by heat stored in weakly screened interfacial charges. Finally, we combined micro-CT imaging with the lattice Boltzmann method to investigate the microscopic characterization and two-phase fluid flow in porous geomaterials.

This dissertation enhances the understanding of non-Darcian flows, reveals hydration hysteresis, and provides a methodology for exploring two-phase flows in clayey porous media.