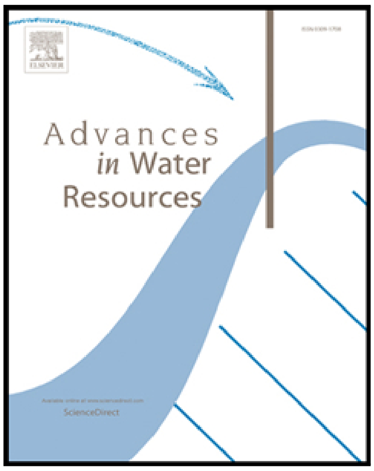

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Erfan A. Amiri, James R. Craig, Barret L. Kurylyk

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A Theoretical Extension of the Soil Freezing Curve Paradigm

Erfan A. Amiri[a,*], James R. Craig[a], Barret L. Kurylyk[b]

[a] *Department of Civil and Environmental Engineering, University of Waterloo, Canada*
[b] *Centre for Water Resources Studies and Department of Civil and Resource Engineering, Dalhousie University, Canada*

Abstract

Numerical models of permafrost evolution in porous media typically rely upon a smooth continuous relation between pore ice saturation and sub-freezing temperature, rather than the abrupt phase change that occurs in pure media. Soil scientists have known for decades that this function, known as the soil freezing curve (SFC), is related to the soil water characteristic curve (SWCC) for unfrozen soils due to the analogous capillary and sorptive effects experienced during both soil freezing and drying. Herein we demonstrate that other factors beyond the SFC-SWCC relationship can influence the potential range over which pore water phase change occurs. In particular, we provide a theoretical extension for the functional form of the SFC based upon the presence of spatial heterogeneity in both soil thermal conductivity and the freezing point depression of water. We infer the functional form of the SFC from many abrupt-interface 1-D numerical simulations of heterogeneous systems with prescribed statistical distributions of water and soil properties. The proposed SFC paradigm extension has the appealing features that it (1) is determinable from measurable soil and water properties, (2) collapses into an abrupt phase transition for homogeneous media, (3) describes a wide range of heterogeneity within a single functional expression, and (4) replicates the observed hysteretic behavior of freeze-thaw cycles in soils.

Keywords: permafrost, ice fractionation, soil freezing function, heterogeneity, soil freezing curve.

1. Introduction

Ground ice influences the mechanical, hydraulic, and thermal properties of soil [1, 2, 3], and thus permafrost thaw can cause soil instability [4, 5] and hydrologic and hydrogeologic changes [6]. Thawing permafrost also acts as a positive climate change feedback by releasing sequestered carbon into the atmosphere [7]. Consequently, quantifying the influence of recent and future global warming on permafrost thaw is an important research topic for climate scientists, hydrologists, and geotechnical engineers [8, 9, 10].

Numerical models are often employed to calculate rates of permafrost thaw because analytical solutions to heat transfer problems involving phase change are limited by their simplifying assumptions [11]. In numerical models, the front tracking approach [12] precisely predicts the location of the phase change interface, and thus it is popular in solidification problems, in which the exact location of the interface between the solid and liquid phase is important. The issue with this method is that it may be impossible to track multiple sharp interfaces of complex shape; alternately, in most porous media, the phase change interface is not sharp. The latter is generally the case for soil freezing and thawing, because pore water phase change is a non-isothermal process due to capillary and sorptive forces, variable solute concentrations, and soil heterogeneities [13]. Thus, the freeze-thaw interface in soil exists as a partially frozen

*Corresponding author. Tel.: +1-519-888-4567 ex. 31162.
E-mail address: eabedian@uwaterloo.ca.