A Model for the Formation of Ice Lenses in an Unconfined, Water-saturated, Porous Medium consisting of Spherical Particles

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ABSTRACT: A model for simulating the formation of ice lenses during freezing of unconfined uniform porous media is presented. The main notions of the model are that generation and jump are dependent on the freezing rate, and that growth is dependent on supercooling. The critical freezing rate is assumed to vary with changes in the number of particles near the ice lens due to the growth of the ice lens. The proposed model was computed for the unidirectional freezing of a porous medium consisting of 10 μm-diameter glass particles. The numerical results show that this model can represent the formation of intermittent layers of ice lenses in the porous medium. This model can be applied to ice formation in unconfined water-soaked porous media.

NOMENCLATURE

a	m	average molecular distance in liquid
A	$m^{-2}s^{-1}$	coefficient in equation (2)
B	$m\ s^{-1}{}^{\circ}C^{-1}$	empirical constant in equation (3)
C	m^{-5}	coefficient in equation (8)
d	m	diameter of the particle
D	m^2s^{-1}	self-diffusion coefficient of water
G	-	specific gravity
k	$J\ K^{-1}$	Boltzmann factor
k	$Wm^{-1}{}^{\circ}C^{-1}$	thermal conductivity
K	$m^2s^{-1}J^{-1}$	hydraulic conductivity near the ice lens
L	$J\ g^{-1}$	Latent heat of ice
N	-	number of particles per unit volume
Q_m	J	the molecular heat of melting of ice
t_p	s	elapsed time
T	˚C	temperature
v	m^3	molecular volume
V_c	$m\ s^{-1}$	critical freezing rate for isolated particle
V_c‘	$m\ s^{-1}$	critical freezing rate in porous media
V_f	$m\ s^{-1}$	rate of advancing freezing front
V_s	$m\ s^{-1}$	constant rate equivalent to the mean of rate of advancing freezing front
w	%	water content by weight
X	m	width of considered rectangular
Y	m	height of considered rectangular
z	m	coordinate
Z	m	length of the rectangular (freezing direction)
α	$m^2\ s^{-1}$	thermal diffusivity
Δγ	$N\ m^{-1}$	difference of surface energy
Δp	Pa	pressure difference
ΔT_{il}	˚C	supercooling degree
η	Pa s	coefficient of viscosity
ρ	$g\ m^{-3}$	density of ice

Subscripts

0	initial	i	ice	u	unfrozen
f	frozen	il	ice lens	w	water
H	high	L	low		

1 INTRODUCTION

When soil is frozen unidirectionally, the soil water sometimes forms regions of ice that are almost devoid of soil particles. These regions are called ice lenses, and repetition of the process results in the formation of intermittent layers of ice lenses (Figure 1a). The formation of ice lenses is recognized as a necessary condition for frost heave and is also reported to occur in other porous media (e.g. Dash *et al.*, 1995; Mutou *et al.*, 1998). This paper focuses on the process of ice formation in porous media consisting of fine particles.

Various models have been developed to describe frost heave (Kujala, 1997). Presently, the model most often used to describe the mechanism of frost heave is the secondary frost heave theory proposed by Miller (1972), since it can explain the formation of intermittent layers of ice lenses. The model emphasizes the importance of ice growing in the frozen fringe, which was assumed to consist of a network of pore ice extending from the base of the warmest ice lens to a position at or near the 0 °C isotherm. However, the configuration of ice in a porous medium depends greatly upon the conditions of freezing and the characteristics of the medium. Watanabe and Mizoguchi (2000) observed the formation of intermittent layers of ice lenses in an unconfined water-saturated uniform porous medium consisting of micro glass particles 9.7 μm in diameter. They found the ice in the medium does not penetrate the warmer pore than the growing ice lens.