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Thermal Boundary Effects On Pattern Formation Due to Differential Frost Heave

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Frost heave can occur in freezing, wet porous media subjected to a temperature gradient. Secondary frost heave of soil includes the description of a partially frozen region, the frozen fringe, within which discrete ice lenses form causing heave. The coupled heat and mass transfer processes have been modeled by several in the past few decades, differing primarily in their explanation of the existence of the supercooled liquid-like layer of water within the frozen fringe, and agreeing on the overall magnitude of heave and lens spacing. Analytic and numerical solutions have also been limited to one dimension, thus avoiding the complicating factor of the rheology of the freezing material. Because of the highly non-linear pressure profile and corresponding non-linear ice content within the fringe, the possibility for complex interactions resulting in pattern formation exists. A linear stability analysis has indicated that multi-dimensional frost heave may indeed spontaneously occur, resulting in differential frost heave (DFH) and pattern formation. The conditions required for DFH are not completely clear, due primarily to uncertainty in describing the rheology of the frozen soil.

We have explored the linear stability problem using both purely elastic and purely viscous constitutive laws to describe the freezing material. We have considered a range of surface thermal boundary conditions including constant temperature, constant heat flux, and a heat transfer coefficient. Results indicate that only a very narrow range of conditions are unstable in the case of constant temperature, requiring a particular porosity and soil type. However, other thermal boundary conditions cause a greater range of instability with larger growth coefficients. The choice of rheology effects the range of unstable modes but not the necessary conditions. A viscous description results in larger patterns in general, while the elastic description is very sensitive to the choice of elastic modulus.

Our inquiry into DFH is driven by the theory that many types of patterned ground observed in the arctic and sub-arctic were initiated by patterns initially inscribed by differential frost heave. It has been shown previously that DFH may contribute to sorted, non-vegetated stone circles, however, the length scales of the patterns have relied on empirical parameterization. Our analysis requires no parameterization of the length scale. We have applied the DFH model to the various conditions in northern Canada and Alaska which have abundant non-sorted patterned ground known as hummocks, mud boils, and frost boils. Presently, a complex physical and biological balance has been established in these regions, while the characteristic pattern length scale varies depending on geographic location. We will discuss how DFH may be implicated in the observed pattern spacing, and observed variability, based on different thermal boundary conditions due to temperature, wind, and snow cover.