Influence of Ice Lens Melt on Permafrost Slumps

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GEOPHYS 228 - Modeling Earth Final Report

1 Problem Definition

Permafrost is defined as soil that has been continuously frozen for at least two years. Permafrost covers around 15% of the Northern Hemisphere, with depths ranging from around a meter to 1,500 meters. This layer of continuously frozen soil usually resides underneath a layer of "active permafrost" that thaws and refreezes seasonally. Beneath the permafrost layer, there is often a layer of unfrozen soil warmed with geothermal heat.

The Arctic is experiencing more significant temperature and precipitation fluctuations than the rest of the world, causing permafrost environments to warm and degrade.[7] With increasing ambient air temperatures, retrogressive thaw slumps (what I refer to as permafrost slumps) are becoming more common. [5] Permafrost slumps are large mass wasting events that are triggered when an ice-rich section of the soil column thaws and reduces stability. This can be triggered by a wide range of factors, including hillside slope orientation and geometry, hydraulic activity in soil column from rivers and groundwater, surface temperature fluctuations, as well as ice content in the soil. The slumps are more commonly seen as landslides occurring on permafrost-rich slopes, but can also occur on relatively flat surfaces.[1]

Permafrost landscapes can become incredibly complex due to the geomorphological processes connected to freeze-thaw cycles. A few interesting landforms include pingos, large mounds caused by ice lenses forming underneath the active layer of soik, ice wedges creating cracks in soil and rock as they expand, and stone rings formed by rock sorting. Since we cannot realistically simplify permafrost environments to an isolated frozen soil column, it is crucial to understand how these different land forms can interact with the permafrost and how they can influence soil stability. [8]

In this project, I aim to investigate the role of an ice lens on permafrost slumps. More specifically, I focus on how the the spike in pore water pressure, due to a large body of ice melting, compares to the overburden pressure - with the assumption that when these two are equal, the soil is fluidized and prone to slump given any applied stress. My hypothesis is that the larger the ice lens is in comparison to the soil column, the deeper the system will become fluidized, and thus the more significant of a slump given that more soil mass would be destabilized.

2 Encoding

To investigate the role of ice lenses on permafrost stability, I attempt to replicate the permafrost system as accurately as possible with an active layer and a frozen layer (assumed to be close to thaw, and thus slightly permeable). The goal is to understand the most extreme impact an ice lens could have on permafrost stability, which I assume to be when it completely melts. Rather than incorporating heat transfer and other thermal effects due to ice thaw, we only focus on how the changes in water pressure affect soil stability.

2.1 Physical Model

We use Darcy's law to model the flow of water in the soil column due to the changing pressure gradient in depth,

$$\vec{w} = \frac{k}{\mu}\frac{\partial P}{\partial z} \tag{1}$$

where k is permeability and P is the total pressure. Instead considering this as a volume flux, and replacing permeability with hydraulic conductivity K, we have

$$\begin{aligned} Q &= -\frac{kA}{muL}\Delta P & (2)\\ &= -K\frac{\Delta p}{\rho g L} & (3) \end{aligned}$$

How pore water pressure affects the soil stability is modeled by the effective stress law from soil mechanics,

$$\sigma' = \sigma_{ov} - \alpha p \tag{4}$$

where σ' is the effective stress, σ_{ov} is the overburden or lithostatic pressure from the weight of the soil. We then relate the increasing pore-water volume to the pore-water stress with an equation derived from Biot's theory of poroelasticity (found in Prof. Dunham's lecture notes on poromechanics),

$$\Delta V_w = \frac{1}{M}\Delta p + \alpha\Delta\epsilon \tag{5}$$

where ΔV_w is the change in fluid volume, M is the Biot modulus, and $\Delta\epsilon$ is the change in volumetric strain of the solid matrix. Here, for simplicity we assume the solid matrix does not deform and thus have

$$\Delta V_w \approx \frac{1}{M}\Delta p. \tag{6}$$

2.2 Geometry & Parameters

The hydraulic conductivity for the active layer K_a is assumed to be $1e-3\frac{m}{s}$, for the permafrost layer K_p is assumed to be much lower, at $1e-6\frac{m}{s}$, and for the water layer we assume the conductivity to be very high with K_w to be $1e-1\frac{m}{s}$. [4] The bulk soil densities are assumed to be ρ_a= 1600 kg/m^3 for the active layer, and ρ_p= 2000 kg/m^3 for the permafrost layer. [9] [3] In this model, I consider both a simple, horizontally homogeneous soil column, and a system where the active layer has some slope to vary the overburden pressure.

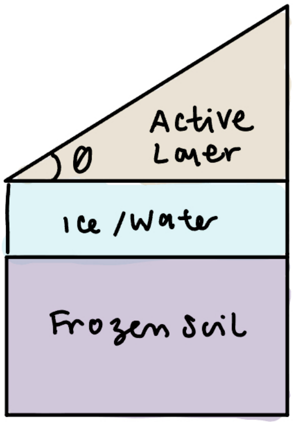

Figure 1: Model Permafrost Soil Column with Slope

3 Analysis

3.1 Numerical Model

I created a simple 2D numerical model of Darcy flow in a permafrost soil column due to the presence of a layer of water. I assume all flow is primarily vertical, and that there is not deformation of the soil matrix. To initialize the pressure gradient, I calculate the overburden pressure profile based on the weight of the soil and assign initial pore-water pressure values to each layer - with a slightly negative value for the active and frozen layer to indicate that it has some water content but is not saturated, and a very high value in the water layer. In the case where the active layer has some slope, the overburden pressure varies in x as well as with depth.

I then use a simple finite-difference scheme to calculate the resulting water flux from the pressure gradient (2), and then update the pore-water pressure using the volume change of water in a cell (6). This loops over a period of several months, or until the pore-water pressure is equal to or higher than the overburden pressure.

3.2 Results

For the model without a slope, as predicted in my intermediate presentation, I was not able to find a slump even with a very high proportion of water.

For the geometry with a slope, I limited the soil column to a relatively small volume with low resolution for ease of computation, of a depth of 10 meters and width of 5 meters. I considered two values for θ, 30 deg and 50 deg. At $\theta = 30$ deg, I was able to see a slump with as a layer of water as small as about a third of the total depth (each layer was about a third of the total depth). And, I did observe that the depth of slump increased as the volume of water increased. Here, we see that for $\theta = 50$ deg.

Figure 2: Ice lens initialized in layers 4-6, slump at layer 5.

Figure 3: Ice lens initialized in layers 4-7. slump at layer 7.

4 Decoding

Verifying these findings, that the presence of an ice lens can contribute to permafrost slump and that the larger the ice lens, the deeper the the slump, is difficult given the lack of data availability on massive ground ice and slump triggers. In a topographical based model studying the central Brooks

Range, an area with low-relief topography, the pore water pressures due to the local hydrology are not enough to trigger a slump and that given the topography, this location is more prone to massive ground ice. However, in this study they could not verify that ice lenses or other forms of segregated ground ice directly caused the slumps and instead used a mechanical model to support that claim. [6]

To isolate this specific finding from the complex open permafrost systems in nature, I decode my results instead using laboratory findings. In [2], both ice wedges (vertical layers of ice) and ice lenses (horizontal layers of ice) were recreated in a laboratory cold-room experiment. Both systems had ice occupying about 30% of total volume, similar to the ratios I used in my model. In both cases, heterogeneous and ice-rich frozen soil showed a faster increase of soil temperature and associated melting compared to a homogeneous and ice-poor frozen soil. With ice lenses, they observed subsidence due to the melting of segregated ice while the homogeneous soil remained stable, verifying my finding that ice lenses do influence permafrost slumps.

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