The Effects of Environmental Controls on Epigenetic Ice Wedge Cracking

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Introduction

Ice wedges and the polygons they form are widespread throughout continuous permafrost regions and are the most common form of massive ground ice. Ice wedges have been a topic of scientific study for almost two centuries, but the factors controlling cracking and the mechanics of the cracking process are not well-understood. The large physical scale and infrequency of cracking events makes in-situ monitoring difficult and precludes laboratory replication.

This project provides a concrete way to compare the application of engineering theory to field observations gained over the past half century. In addition, understanding the cracking characteristics of ice wedges can help inform scientists on the distribution of ground ice within the continuous permafrost region.

Methods

Extended finite element analysis (XFEM) was chosen as a robust method of dividing the large soil model into many smaller pieces (elements) whose behaviour is much easier to calculate. These small pieces together are known as the mesh.

- 40m x 15m soil block with a semi-randomized surface and quadrilateral mesh.
- Soil mechanical model includes elasticity, creep, tensile damage, and thermal expansion.
- Temperature data from ground loggers is applied at the surface boundary with a 40-year spinup.
- The maximum stress at the surface is taken as a simple indicator of whether or not cracking is likely to occur.

How do ice wedges form?

When cracks occur in permafrost, the following spring will deposit meltwater into these cracks to form an ice vein. Ice is significantly weaker than frozen soil, so it will crack in the same location. After many years of this cycle, a large ice wedge is grown! The figures below show a drawing of ice wedge formation (fig.1) and its modeled counterparts (fig.2a, 2b).

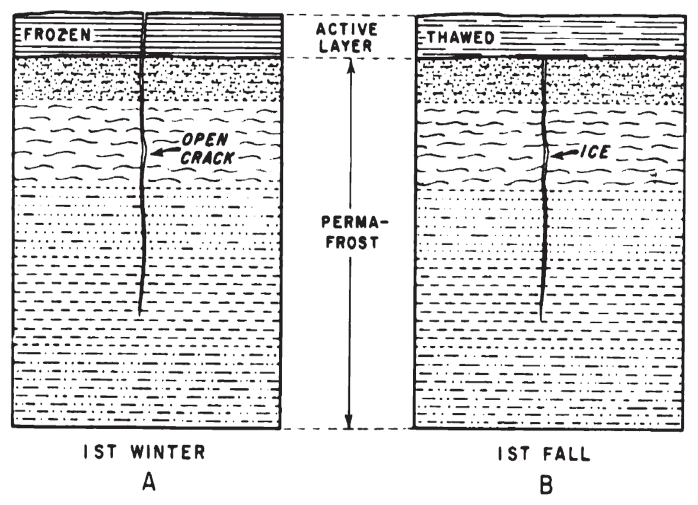
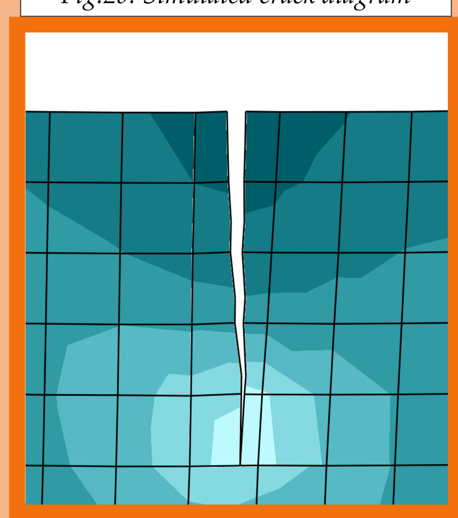


Fig.1: Wedge after one year, and 500 years[1]

Fig.2b: Simulated crack diagram



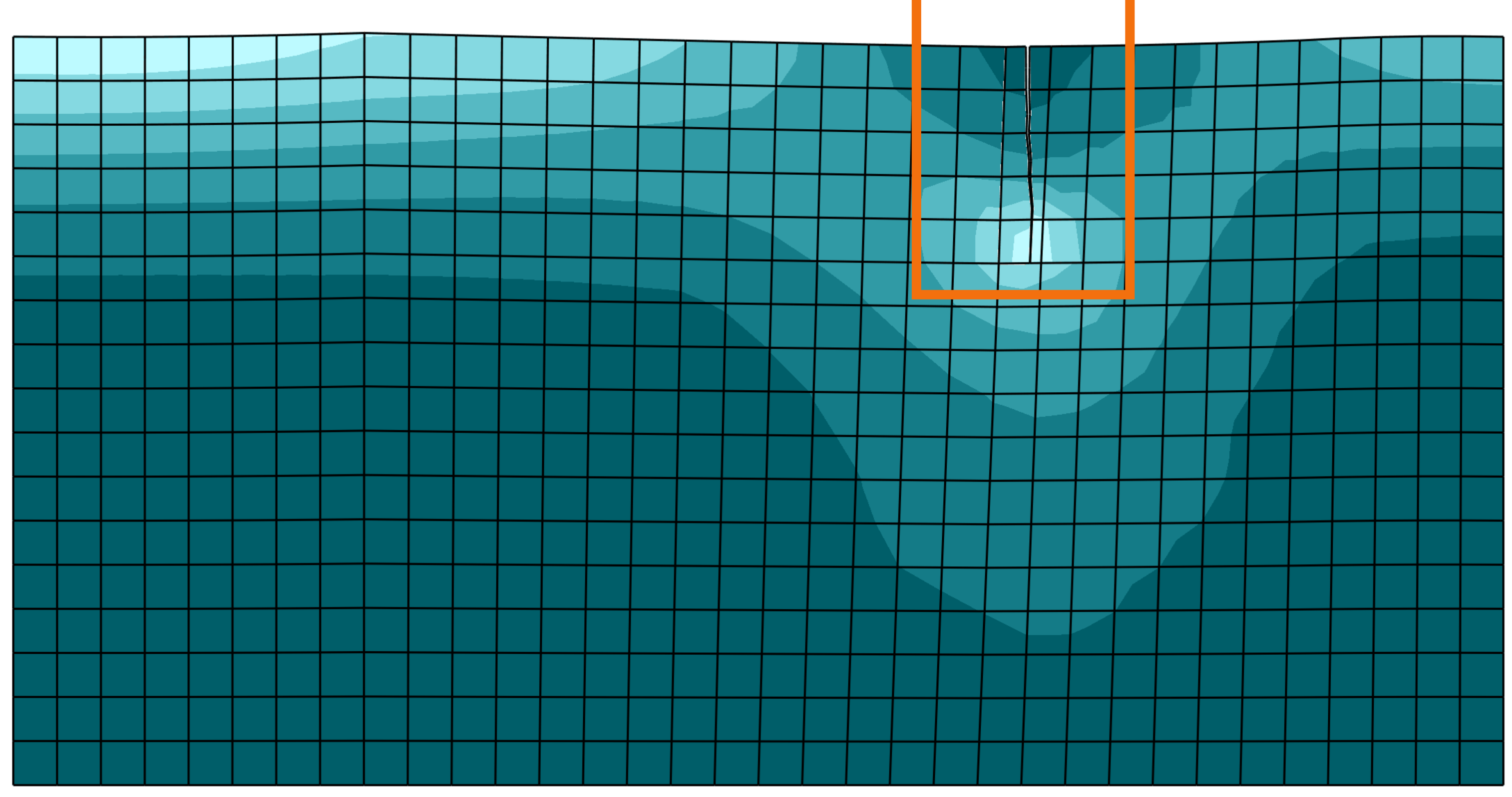


Fig.2a: Model after cracking showing stress distribution, with light blue indicating regions of high stress.

Which parameters have the greatest effect on ice wedge cracking?

<u>Soil type:</u>

- Four different soil types are chosen which represent varying particle sizes: coarse sand, fine sand, silt, and clay. Each soil has different mechanical and thermal properties such as tensile strength, latent heat, and creep. These properties all have an effect on the buildup of stress in the soil.

<u>Freezing characteristic curve (FCC):</u>

- The FCC is closely related to soil type and water content. As water freezes in a saturated medium, such as the ground, it causes the medium to expand as the water turns to ice. This effect is shown to cause increased stress at the surface.

<u>Temperature series:</u>

- Temperature is the main driving factor behind ice wedge formation. Temperature series from sites in the same region are compared to determine the effect of microscale variations.

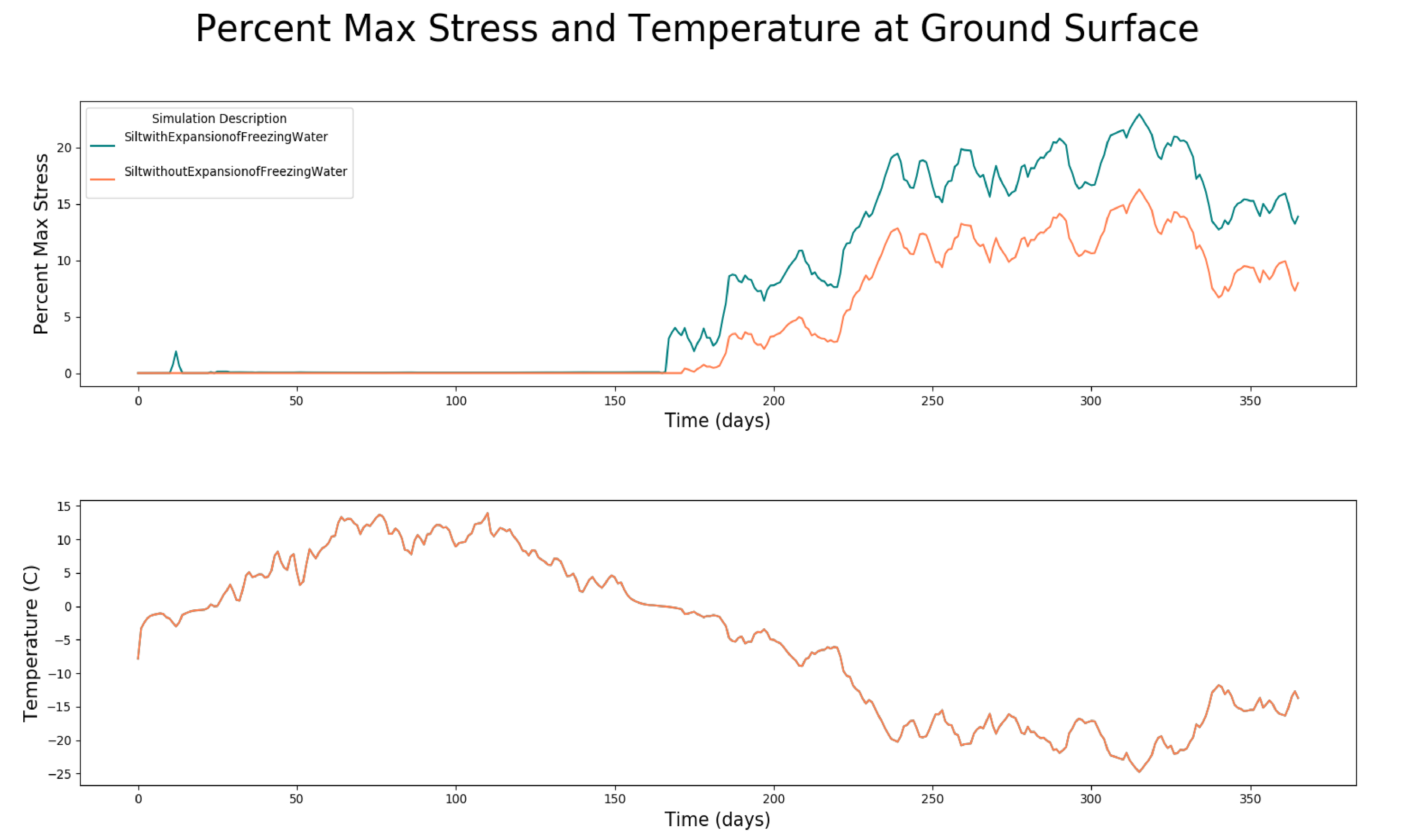


Fig.3: Temperature and stress over time, with and without the effect of the expansion of freezing water

Results

- Incorporating the expanding effect of freezing water leads to significantly higher stresses at the ground surface (fig 3).
- Temperature series with lower average temperatures generate greater stress (fig 4).
- All sites are found in the same region with the same air temperatures, showing that microscale effects are significant on stress generation (fig.4).
- The four soil types do not have an absolute stress ranking. For example, coarse sand may generate more stress than fine sand for some temperature series but not for others (fig.4).

Max Percent of Cracking Stress Recorded at Ground Surface

Soil Type, Site Description	**1005:** Medium-low vegetation, relatively cool ground	**168:** medium-high vegetation, ground relatively warm	**2004:** low vegetation, on a hilltop, ground relatively cool	**2029:** low vegetation and bare, esker top, ground cold
Coarse sand	23	12	20	28
Fine sand	21	13	20	30
Silt	19	10	18	25
Clay	24	11	22	33

Fig.4: Stress comparison, with light blue indicating higher maximum stress

Discussion

- Lower temperatures lead to greater stresses. Partly because the coefficient of thermal expansion causes the ground to contract further as temperature decreases and partly because soil becomes stiffer as temperature decreases and viscoplastic effects do not dissipate stress as readily.
- No one soil property has been identified as the main stress controller. All mechanical properties play a different role in stress generation and combine to produce unique results.
- The effect of freezing water expanding at depth in the ground causes the soil above to be pulled apart, leading to greater stresses at the surface.

Next Steps

- Investigate how the depth and spacing of ice wedges vary with the above parameters and create a Python script to automatically measure these variables during simulations.
- Compare the simulated depth and spacing to field observations and analytical solution to gauge the accuracy of the simulation.
- Run long-term simulations of ice wedge formation to determine whether this simulation method can replicate the trough formation commonly found in ice wedge polygons.

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References:
[1] Lachenbruch, A. H. (1963). *Contraction theory of ice-wedge polygons: A qualitative discussion.* MacOdrum Library.