Modeling the Effects of Pore-Water Phase Change on Ice-Wedge Cracking

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Introduction and Background

Summary

Ice-wedge polygons are a widespread landform throughout continuous permafrost regions and form through thermal contraction-cracking of frozen soil. This process is influenced by environmental factors such as soil type, site hydrology, climate, and snow. In particular, the mechanical effect of variations in soil water content has not been well-investigated.

We present a numerical model to simulate thermal contraction-cracking based on the analytical solution by Lachenbruch[1], which is able to reproduce cracking events in permafrost and the subsequent creation of ice wedges. We explore the modeled effects of the freezing volumetric expansion (FVE) of water on contraction-cracking and extend these findings to soil water content.

Thermal Contraction-Cracking

Thermal contraction-cracking occurs during the winter months as temperatures decrease and frozen soil becomes brittle. The following spring, meltwater infiltrates the crack and freezes in contact with permafrost to form an ice vein. Figures 1 and 2 compare diagrams from the analytical solution to the thermal contraction-cracks produced by our model[1].

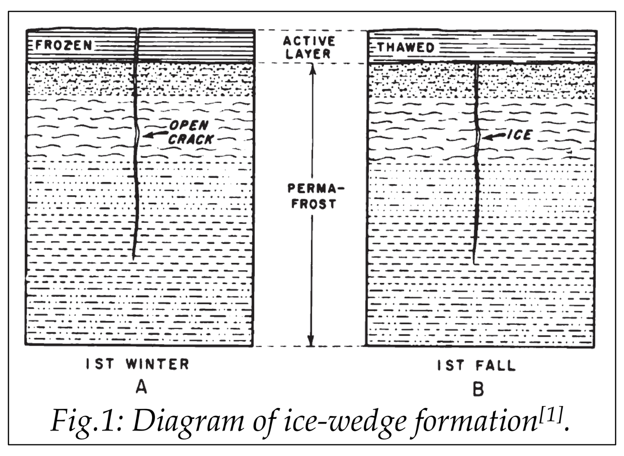


Fig.1: Diagram of ice-wedge formation[1].

Fig.2b: Crack close-up.

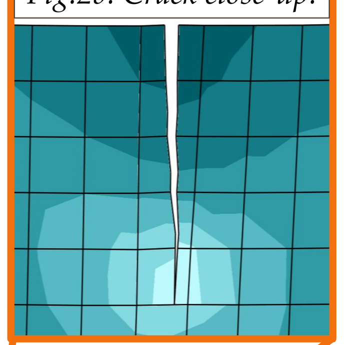
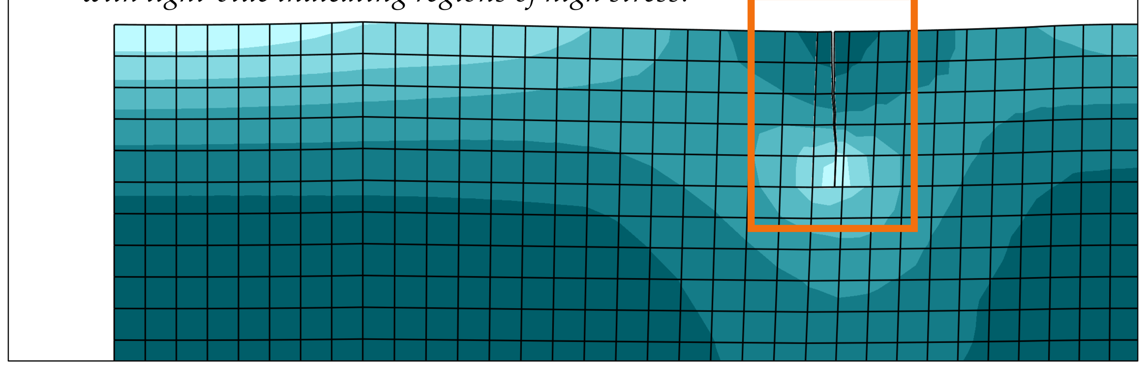


Fig.2a: Model after cracking showing stress distribution, with light-blue indicating regions of high stress.



Freezing Volumetric Expansion (FVE)

As water freezes in a saturated medium, it causes a volume change, or *volumetric strain*. The characteristics of the imposed strain depend on the degree of saturation and the type of soil (Fig.3).

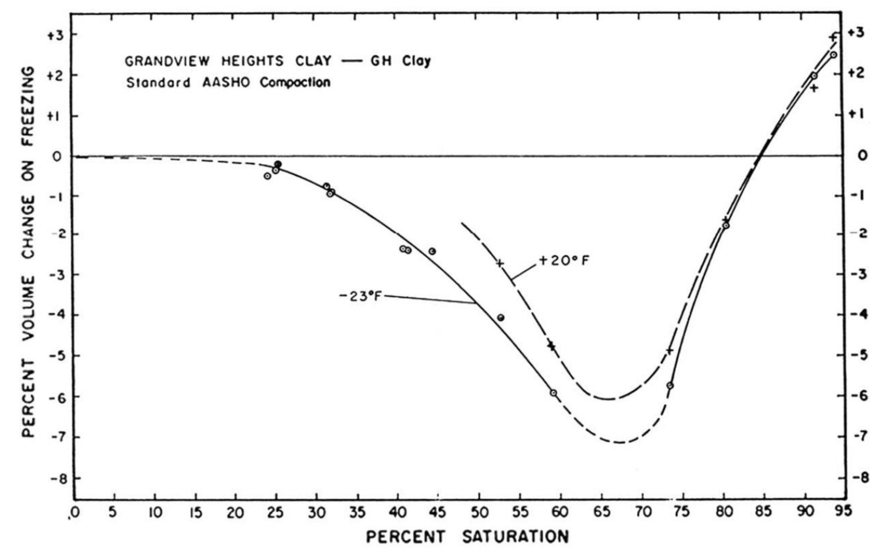


Fig.3: Soil volume change upon freezing[3].

Here, we focus on fully saturated soils, which produce an expansive volumetric strain of 2-3% upon freezing. Inputting this behaviour into the model via the coefficient of thermal expansion allows us to study its effects.

To isolate the effect of the FVE, we implement two different coefficients of thermal expansion: α is the control, representing <u>unsaturated</u> soil, and α_{app} integrates the effect of the FVE, representing <u>saturated</u> soil.

Methods

Model Implementation and Parameters

- We use four soil types, each with different grain size distributions and water contents: Ottawa Sand, Manchester Fine Sand, Hanover Silt, and Suffield Clay.
- Water within soil does not freeze instantly at 0°C, but over a range of temperatures. This behaviour is described by the **freezing characteristic curve** (Fig. 3).
- These parameters have been calculated from the Van Genuchten[2] model, based on the soil particle-size distribution.

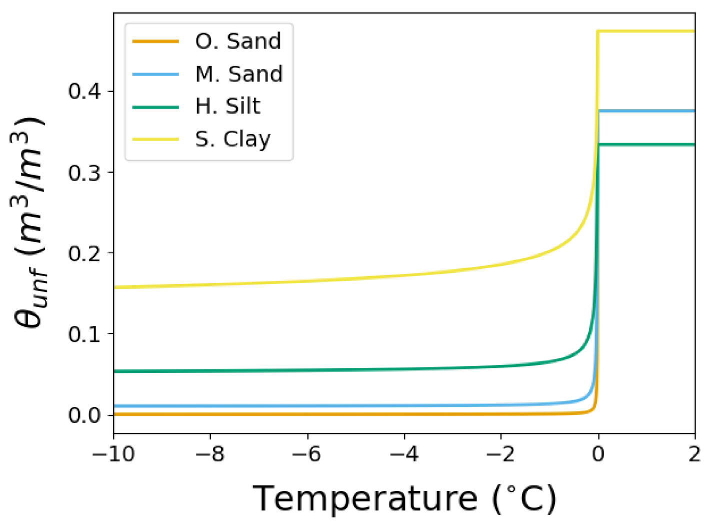


Fig.3: Freezing characteristic curves for the four soils. The y-axis denotes unfrozen volumetric water content.

Coefficient of Apparent Thermal Expansion

The effect of the FVE is integrated into the thermal expansion coefficient for each soil (α_{app}) using the following equation:

$$\alpha_{app} = \alpha + (-0.09)\,\beta\,\frac{d\theta_u}{dT}$$

- Where α is the original coefficient of thermal expansion (α = 0.00003/°C).
- θu / dT is the slope of the freezing characteristic curve (Fig. 3).
- β is a factor to account for anisotropic expansion (β = 0.2).

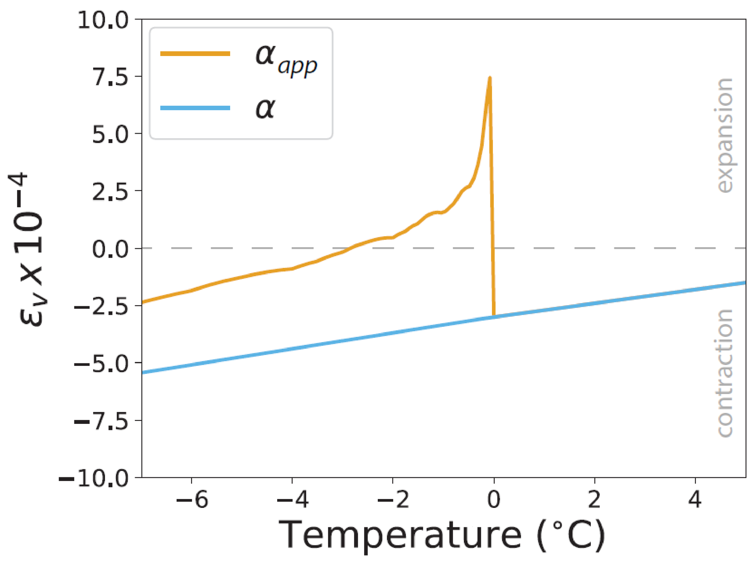


Fig.4: Comparing volumetric strain (ε_v) for S. Clay using different coefficients of thermal expansion. ε_v is the integral of thermal expansion with respect to temperature.

Model evaluation

Stress at the surface is the criterion for thermal contraction-crack initiation, as new ice wedges are shown to initiate at the ground surface.

With this in mind, we developed a new metric to compare simulation results, called **<u>cracking potential.</u>** This is given as the stress at the surface divided by the fracture strength of a given soil.

Higher cracking potential indicates an increase in the likelihood of thermal contraction-cracking.

Model Results

For each coefficient of thermal expansion, four different soil types and four temperature series (A-D) are used. Series are ordered by mean annual ground surface temperature (MAGST) where A is the warmest and produces the lowest cracking potential, while D is the coldest and produces the highest potential.

Figures 5 and 6 compare the cracking potential for all 32 combinations of soil type, temperature series, and coefficient of thermal expansion.

Results

α	Temp A	Temp B	Temp C	Temp D
O. Sand	8.5	52.3	78.8	189
M. Sand	12.3	41.8	65.8	150.3
H. Silt	27.3	56.5	68.6	139.5
S. Clay	20.1	60.3	90.7	223.9

Fig. 5: Maximum cracking potential using α for four soil types and temperature series. Control tests.

α_{app}	Temp A	Temp B	Temp C	Temp D
O. Sand	44.8	86.8	102.6	248.6
M. Sand	72	74	90.3	205.2
H. Silt	82.7	91.6	103.3	187.1
S. Clay	50.1	117.9	149.7	293.3

Fig. 6: Maximum cracking potential using α_{app} for four soil types and temperature series.

- For all simulations, α_{app} produces much higher cracking potential.
- The effect is most prominent for S. Clay.

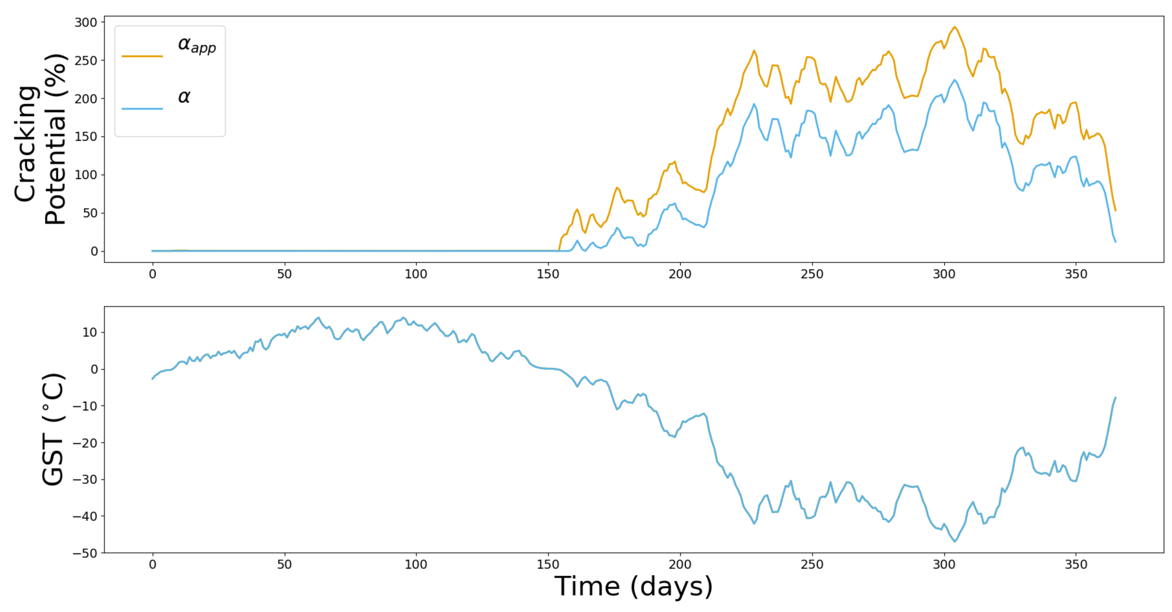


Fig.7: Model stress over time using α_{app} and α, with temperature.

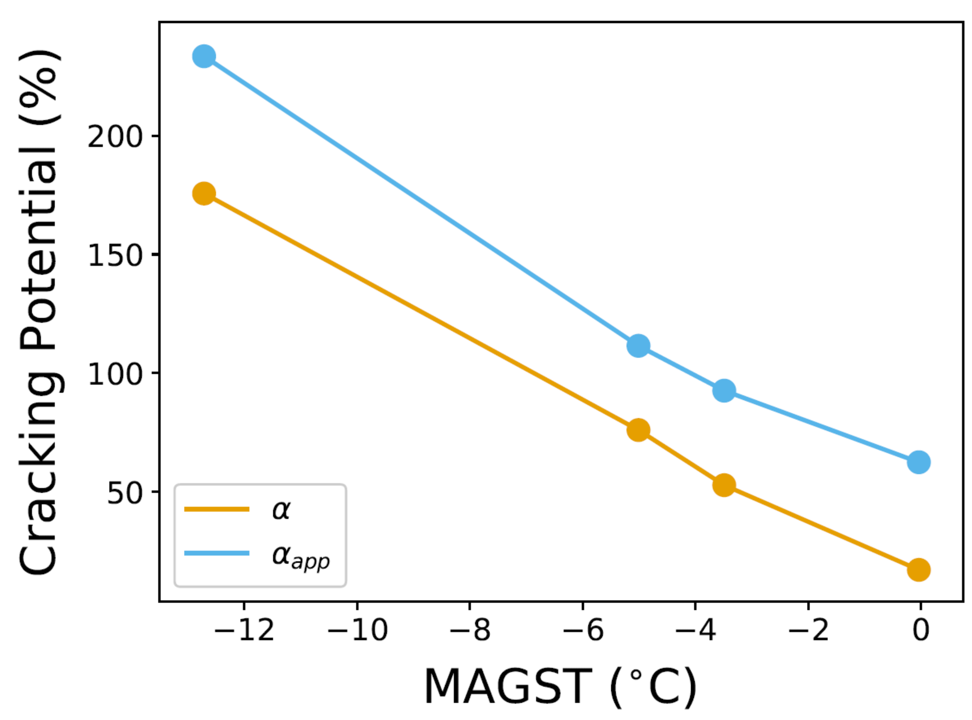


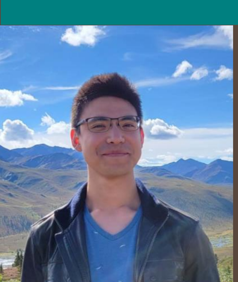
Fig.8: Maximum generated model stress as a function of MAGST. Values from Figs. 5, 6 are averaged for each temperature series A-D.

Conclusion

Using the model results, we can infer some effects of soil saturation on thermal contraction-cracking. Where α_{app} is closely related to a saturated soil and α to an unsaturated soil.

- Saturated soils (α_{app}) consistently produce higher cracking potential at the surface than their unsaturated (α) counterparts. This was true in all simulated cases.
- The difference in cracking potential is equivalent to a difference in MAGST of 3°C (Fig. 8). In other words, a saturated soil is as likely to crack as an unsaturated soil in a climate 3°C cooler. This may help explain wedges which continue to crack after developing ponds, despite the increase in temperature that ponding causes[4].

Understanding site conditions such as water content, in addition to soil type and climate, can provide new insight into predicting thermal contraction-cracking in the field.



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[1] Lachenbruch, A. H. (1963). *Contraction theory of ice-wedge polygons: A qualitative discussion*.
[2] Dall'Amico, M. et al. (2011). *A robust and energy-conserving model of freezing variably-saturated soil.*
[3] Hamilton, A. B. (1966). *Freezing shrinkage in compacted clays.*
[4] Mackay, J. R. (1992). *The frequency of ice-wedge cracking (1967–1987) at Garry Island, western Arctic coast, Canada*.