Environmental Controls on Epigenetic Ice-Wedge Cracking

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Summary

Ice-wedge polygons are a widespread landform throughout continuous permafrost regions and are formed through thermal contraction-cracking of frozen soil. The mechanics of the cracking process are not well-understood as the large physical scale of ice wedges and infrequency of cracking events makes in-situ monitoring time-consuming and precludes laboratory replication.

We present a numerical model to simulate contraction cracking, based on the analytical solution presented by Lachenbruch [1]. This model focuses on the first cracking events in existing permafrost and the resulting epigenetic wedges that form. Three separate case studies investigating different environmental controls and the performance of the model are presented below, with the resulting discussion/conclusions for each study.

How do ice wedges form?

Thermal contraction-cracking occurs during the winter when temperatures decrease and frozen soil becomes brittle as a result. The following spring, meltwater infiltrates the crack and freezes in contact with permafrost to form an ice vein. Ice is weaker than frozen soil, so subsequent cracks form in the same location. Figs. 1 and 2 show the wedge-growth process.

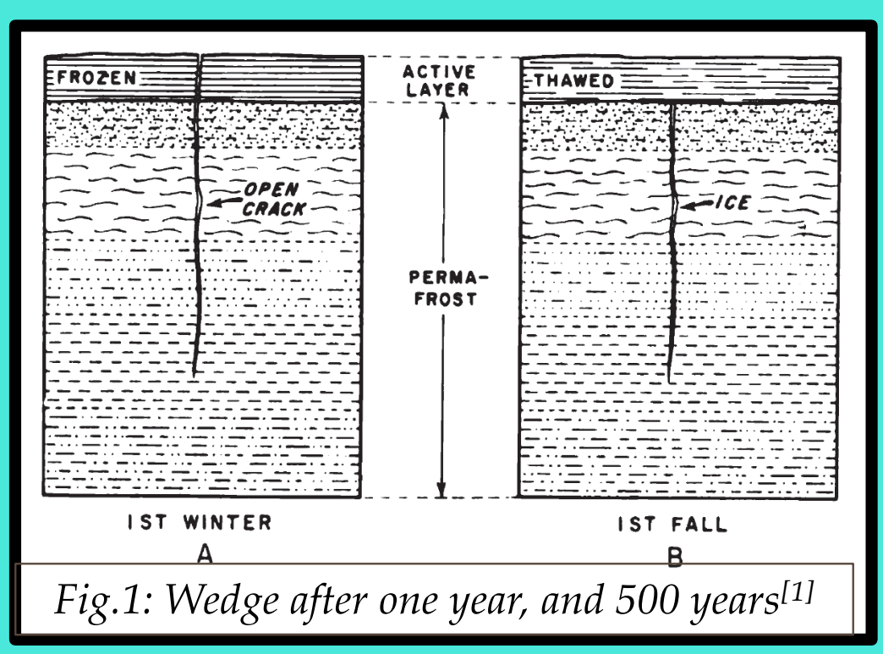


Fig.1: Wedge after one year, and 500 years[1]

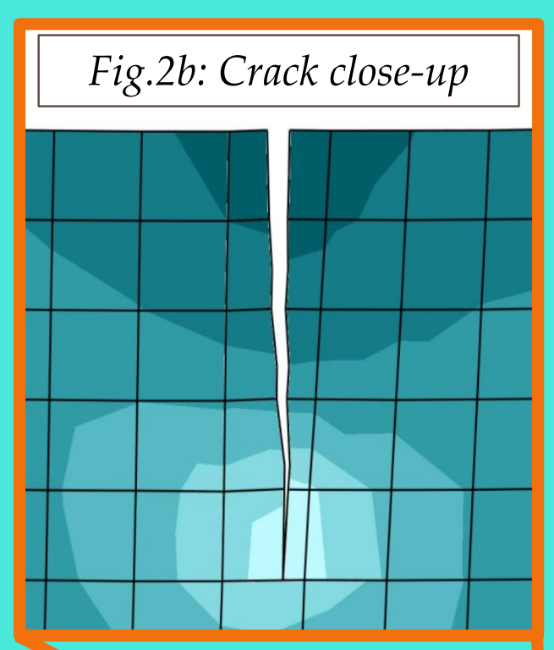
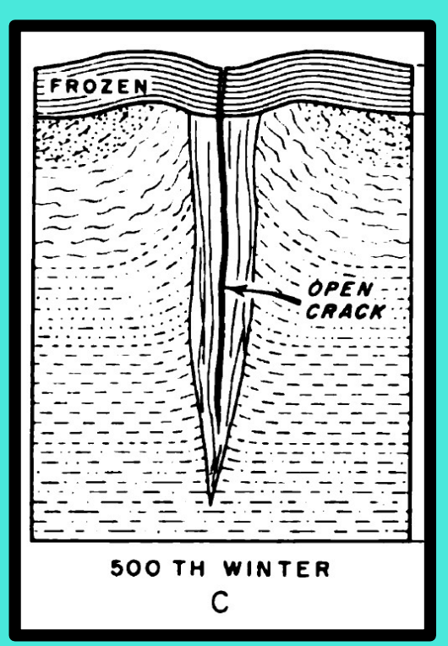


Fig.2b: Crack close-up



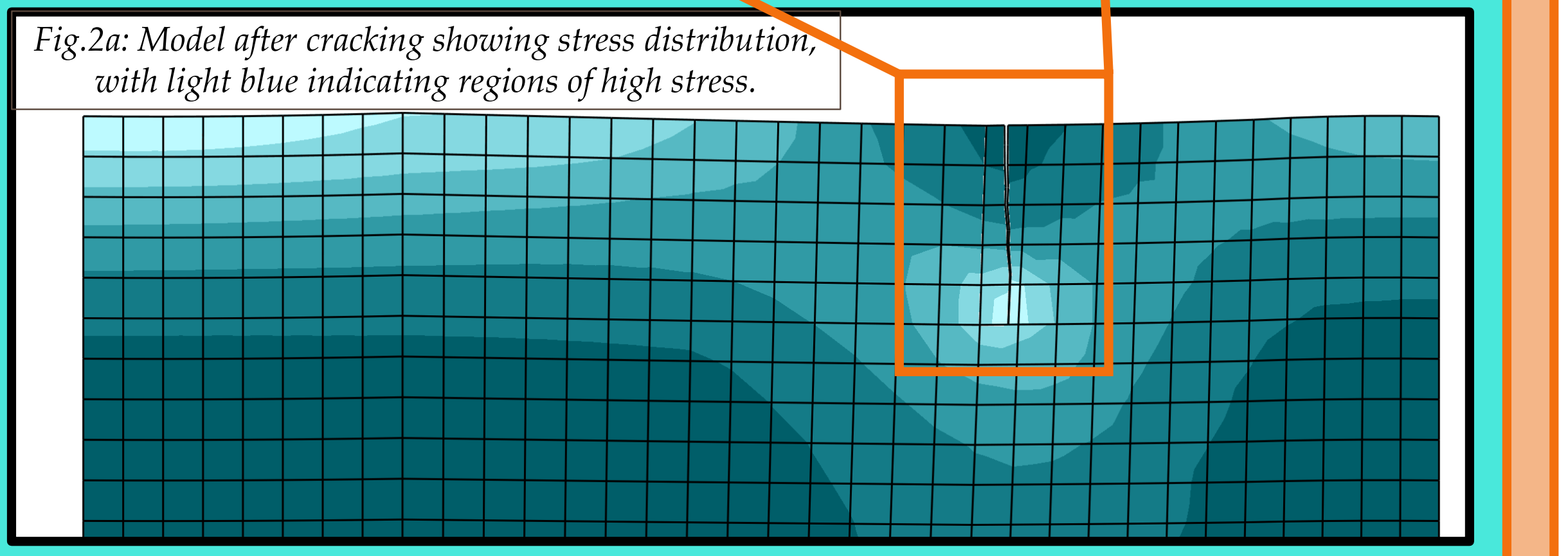


Fig.2a: Model after cracking showing stress distribution, with light blue indicating regions of high stress.

Selection of Environmental Controls

Soil type: Four different soil types are chosen with varying particle sizes: coarse sand, fine sand, silt, and clay. The soils are herein referred to as O. Sand, M. Sand, H. Silt and S. Clay. Each soil has different mechanical and thermal properties, leading to different stress responses.

Climate: Temperature change is the main driving factor behind thermal contraction-cracking. Four temperature series from the Yellowknife region are used as driving data, listed as Temp A-D (Fig. 3) in order of descending mean annual ground surface temperature (MAGST).

Saturation: As water freezes in a saturated medium, it causes the medium to expand as the water turns to ice. This expansion has effects on the generation of stress in soil, which leads to thermal contraction-cracking.

Methodology

- Uncoupled thermo-mechanical simulations use the eXtended Finite Element Method.
- Temperature data drives a thermal model, which is then applied to a mechanical model to induce cracking.
- Temperature-dependant material properties are defined for the four different soil types using existing laboratory studies. In some cases, where data was unavailable, data was adapted from similar studies. For example, tensile strength is adapted from compressive strength data using a modification factor.

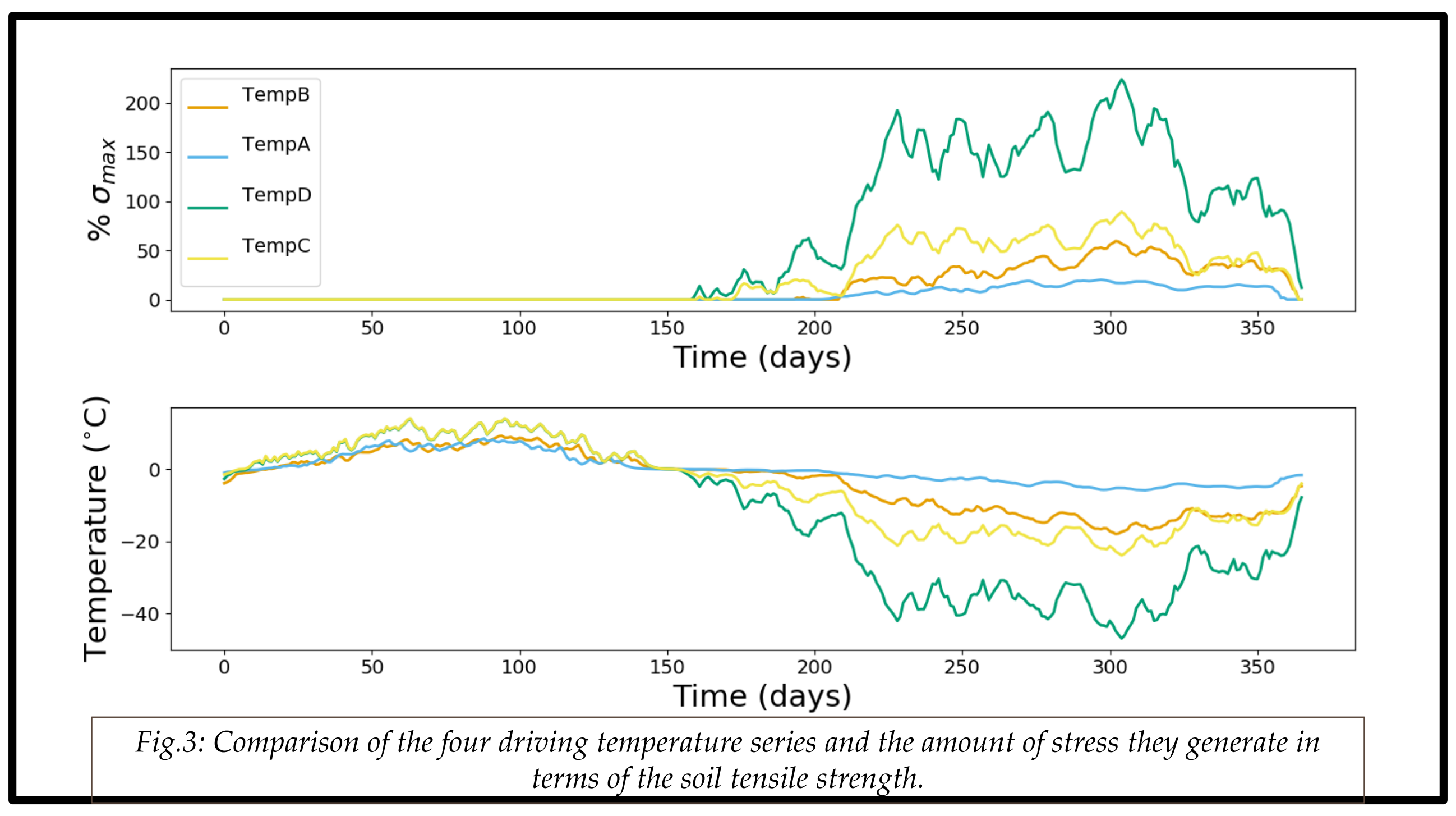
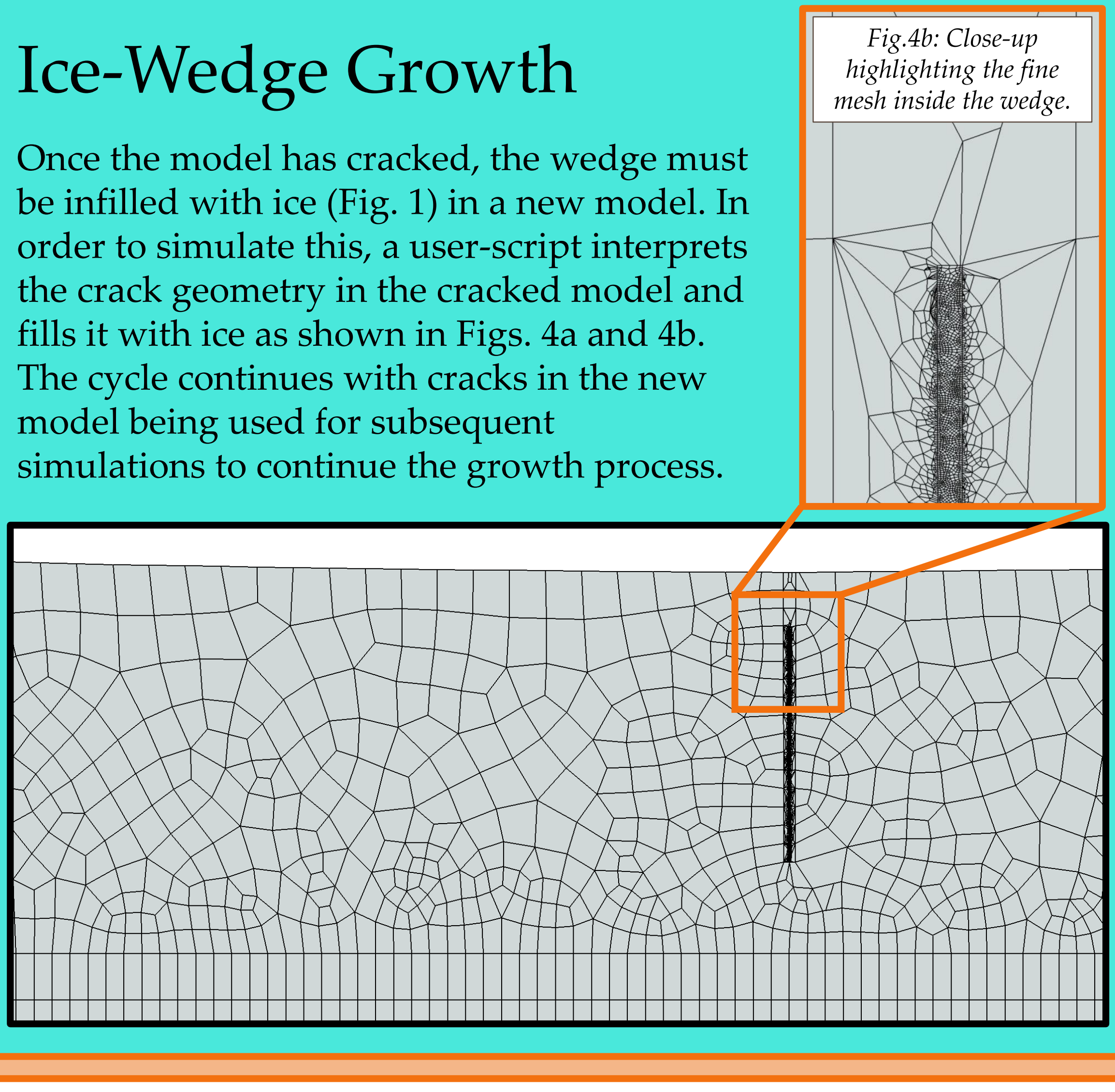


Fig.3: Comparison of the four driving temperature series and the amount of stress they generate in terms of the soil tensile strength.

Ice-Wedge Growth

Once the model has cracked, the wedge must be infilled with ice (Fig. 1) in a new model. In order to simulate this, a user-script interprets the crack geometry in the cracked model and fills it with ice as shown in Figs. 4a and 4b. The cycle continues with cracks in the new model being used for subsequent simulations to continue the growth process.

Fig.4b: Close-up highlighting the fine mesh inside the wedge.



1. Model Testing

In order to determine the plausibility of model results, they must be compared to existing field data. Three sets of comparisons were performed using the uncalibrated model: crack spacing & depth, crack width, and soil temperature profile. Figs. 5a and 5b provide straightforward comparisons of the ranges of crack spacing and depth; Fig. 6 shows the simulated changes in crack width over the year compared to data from Sarrazin & Allard[2] on Bylot Island; and Fig. 7 compares soil temperature profiles for each series A-D with a limit profile derived from field observations at times of cracking. Profiles to the left of the limit are likely to crack, while those on the right are not.

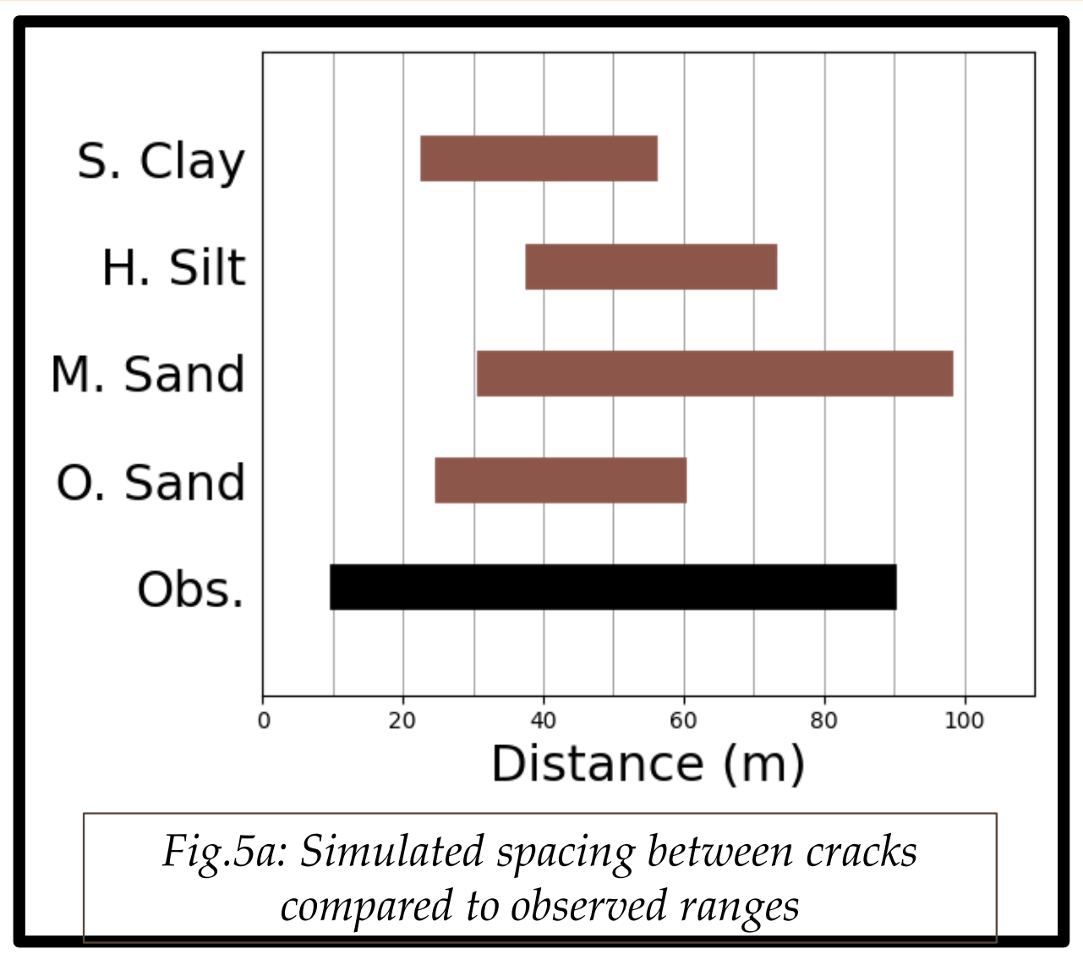


Fig.5a: Simulated spacing between cracks compared to observed ranges

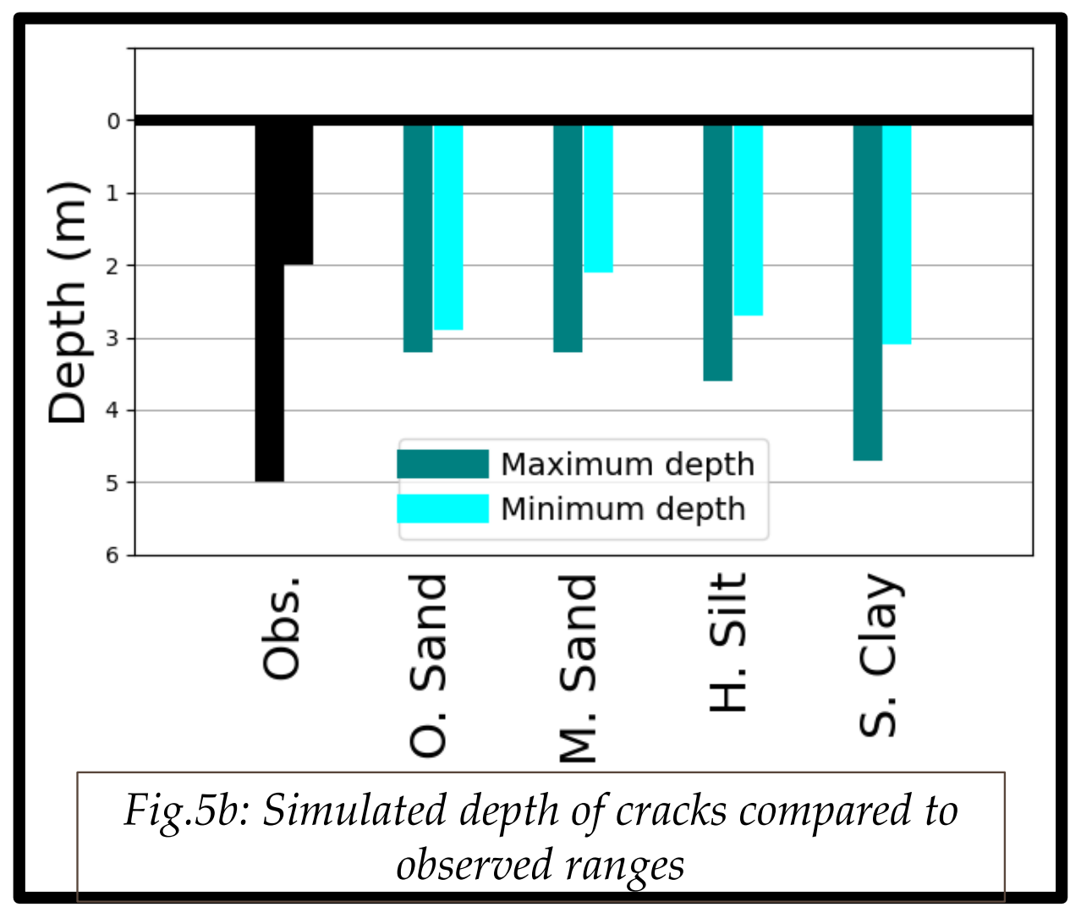


Fig.5b: Simulated depth of cracks compared to observed ranges

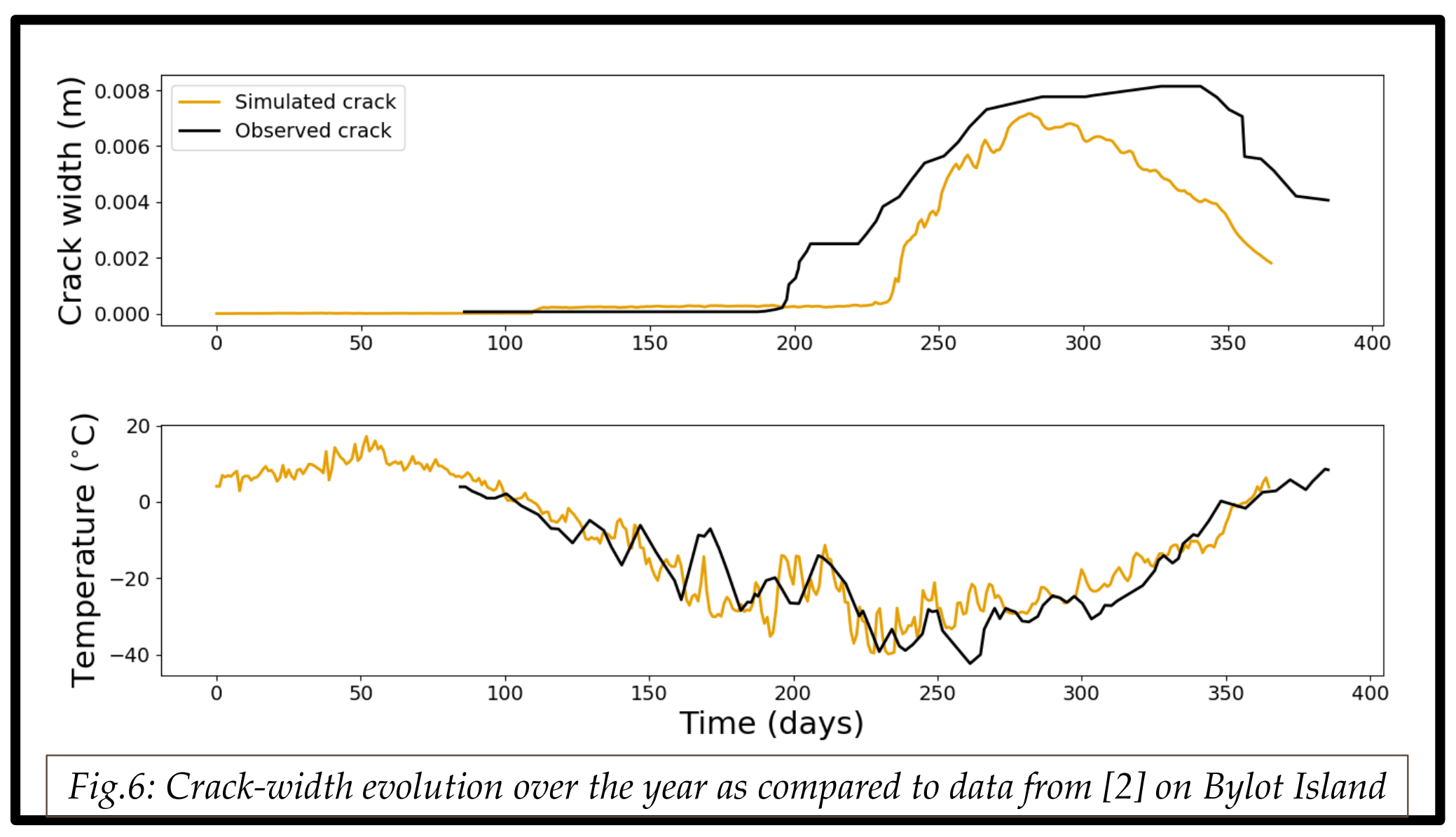


Fig.6: Crack-width evolution over the year as compared to data from [2] on Bylot Island

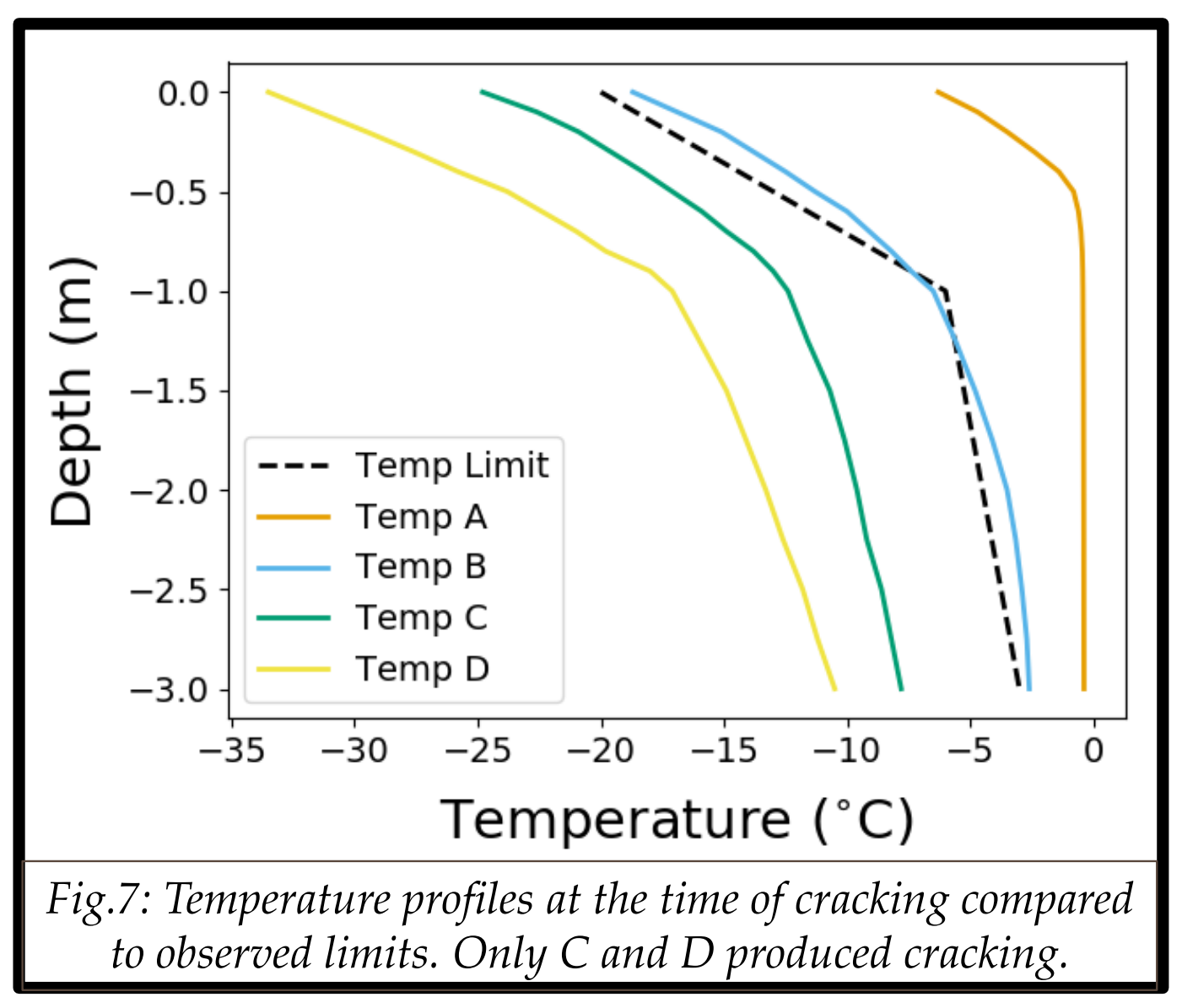
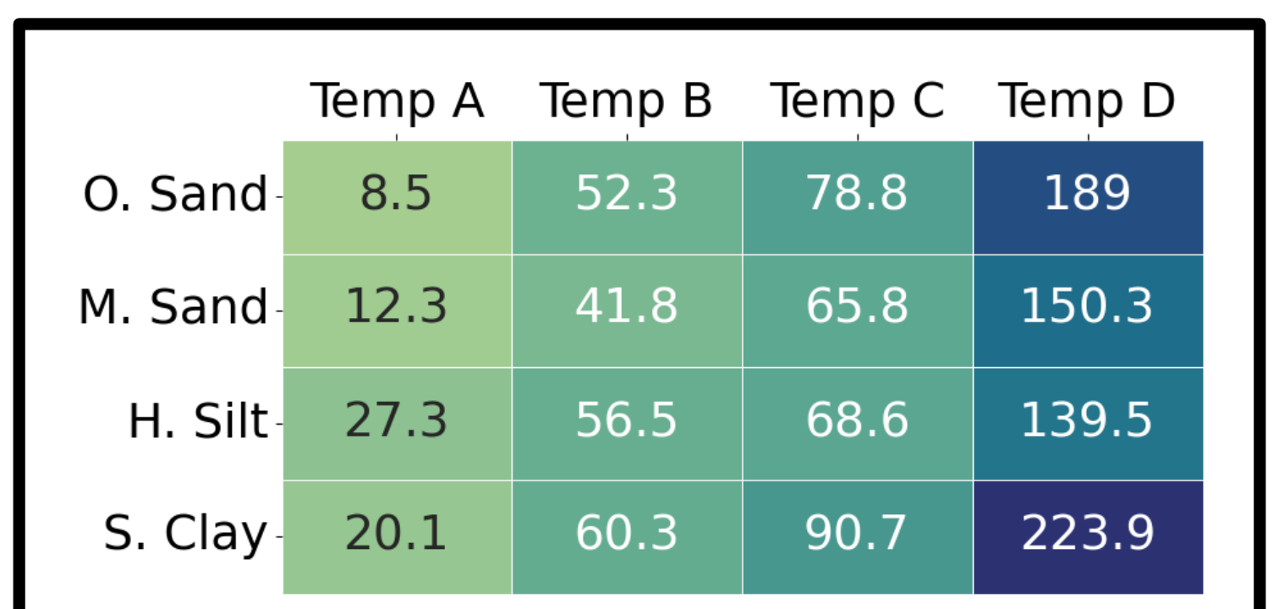


Fig.7: Temperature profiles at the time of cracking compared to observed limits. Only C and D produced cracking.

2. Temperature and Soil Type

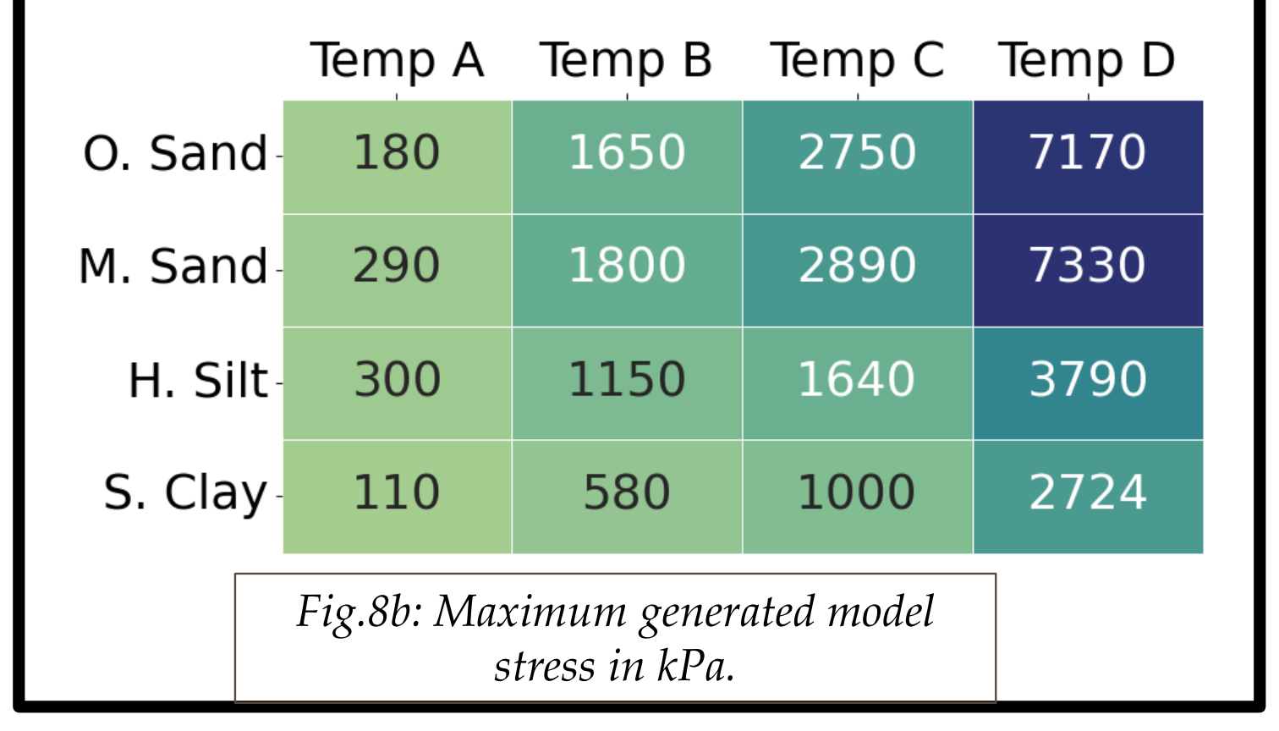
While thermal-contraction cracking is the process of interest, its results can be difficult to quantify in a parametric study. To compare the effects of climate and soil type on cracking, tensile stress generation was chosen as the most appropriate metric. As cracking is directly related to the amount of stress generated in the soil, the results can be interpreted as measures of "cracking potential". Fig. 3 visualizes the four temperature series and their stress generation over a simulation cycle.

For these simulations, cracking was removed, and the observed stresses are reported both in kilopascals (kPa) in Fig. 8a and as a percentage of the fracture strength of the soil in Fig 8b. The heatmaps provide a visualization of the trends of climate and soil type; these trends differ between the two heatmaps due to the different fracture strengths of each soil.



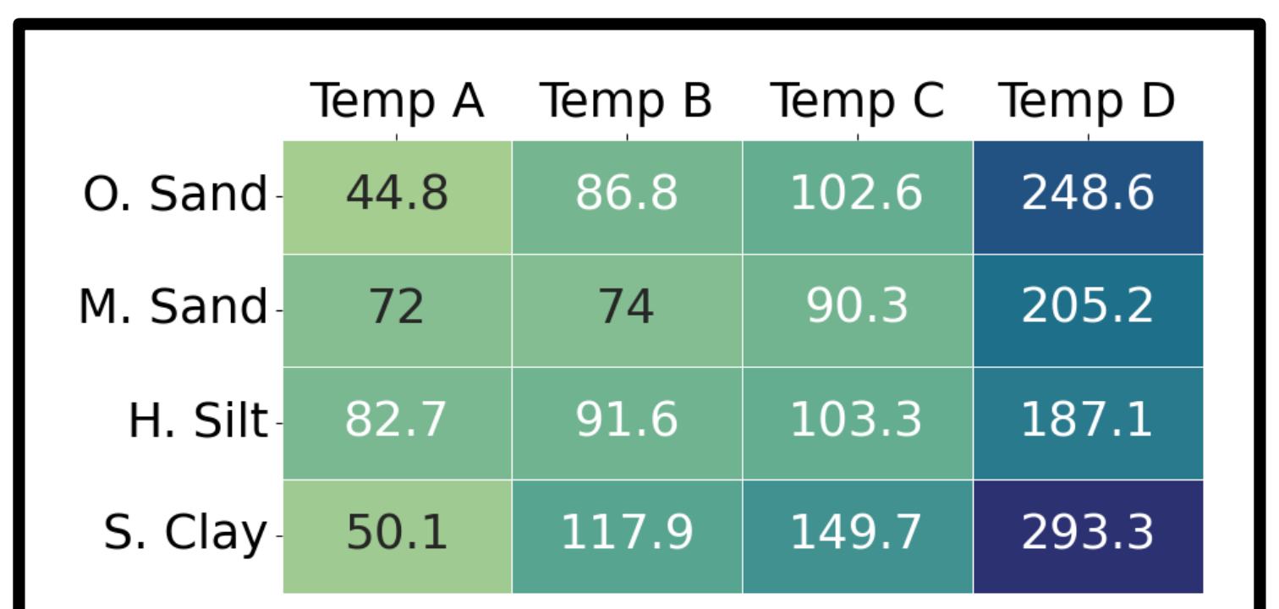
	Temp A	Temp B	Temp C	Temp D
O. Sand	8.5	52.3	78.8	189
M. Sand	12.3	41.8	65.8	150.3
H. Silt	27.3	56.5	68.6	139.5
S. Clay	20.1	60.3	90.7	223.9

Fig.8a: Maximum generated model stress as a percentage of soil fracture strength.



	Temp A	Temp B	Temp C	Temp D
O. Sand	180	1650	2750	7170
M. Sand	290	1800	2890	7330
H. Silt	300	1150	1640	3790
S. Clay	110	580	1000	2724

Fig.8b: Maximum generated model stress in kPa.



	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.8c: Maximum generated model stress as a percentage of soil fracture strength for a saturated model.

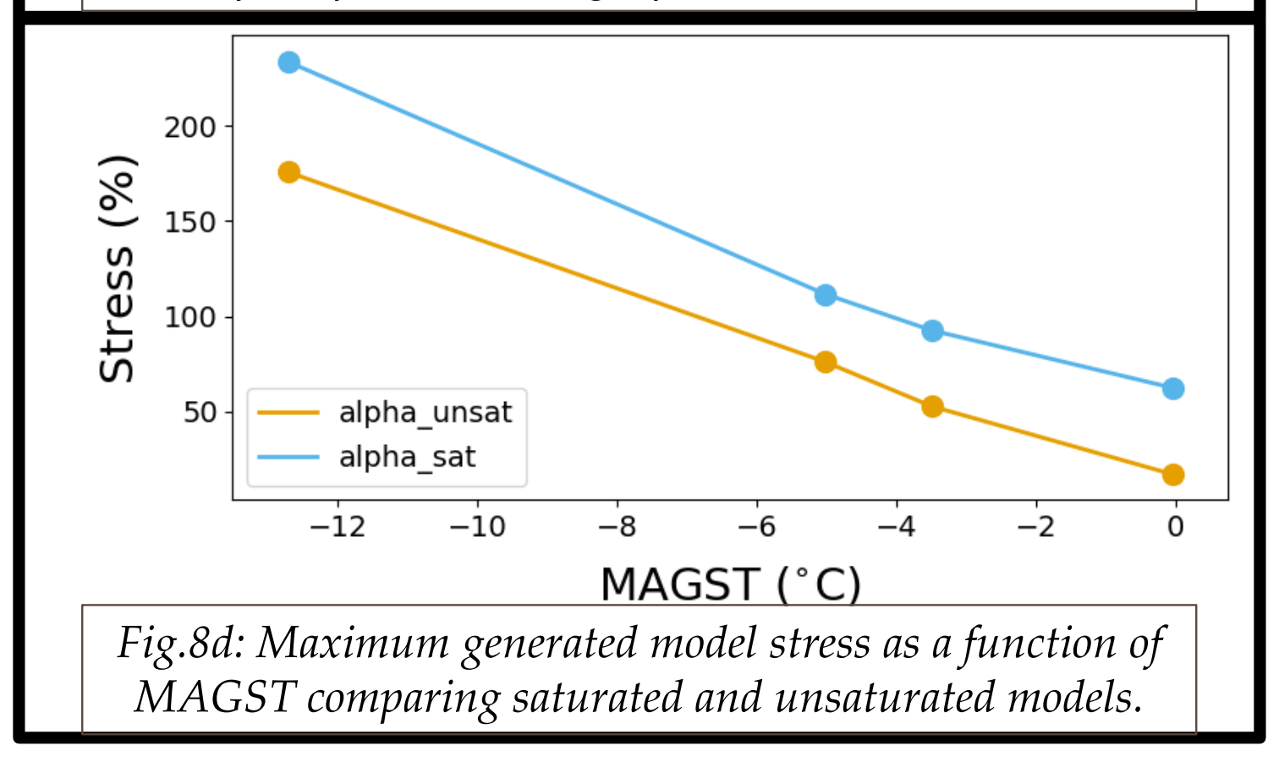


Fig.8d: Maximum generated model stress as a function of MAGST comparing saturated and unsaturated models.

3. Saturation

In **(2)**, an unsaturated model is used to perform a parametric study on climate and soil type. For **(3)**, the same study is performed with a saturated model. In the saturated model, the ~9% expansion of water is considered in the simulation whereas in the unsaturated model it is ignored; unsaturated soils have unfilled void space that can absorb the expansion of water.

The maximum stress generated by these simulations is shown in Fig. 8c. Fig. 8d provides a comparison of Figs. 8a-c as a function of MAGST, with each point representing the max. stress of a different temperature series.

Model Testing

- The model produced plausible results for each of the three scenarios, indicating it is suitable to be applied to different case studies.
- In particular, the model is able to reproduce the slow rate of crack-opening present in the field (Fig. 6). It is often assumed that contraction-cracking happens instantly, but this is not the case. Frozen soil is often too ductile to produce fast fracture speeds.

Temperature and Soil Type

- Coarse-grained soils tend to generate far more stress than fine-grained soils under the same temperature conditions, but this is compensated for by their greater tensile strength, resulting in similar cracking potential.
- Sites A-D are located within a 25km radius with similar air temperatures. The large differences in stress between them indicate the strong effect of microscale variations on ice-wedge formation.

Saturation

- The saturated models which considers the expansion upon phase-change of water consistently produce higher tensile stresses at the surface than their unsaturated counterparts.
- The results suggest that saturated soils produce similar stresses to unsaturated soils with MAGST three degrees lower (Fig. 8d). This may help explain wedges which continue to crack with ponding and

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References:
[1] Lachenbruch, A. H. (1963). *Contraction theory of ice-wedge polygons: A qualitative discussion*.
[2] Sarrazin, Denis, and Michel Allard. "The thermo-mechanical behavior of frost-cracks over ice wedges: new data from extensometer measurements." 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, Quebec City, Canada. 2015.

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