A Study of Thermal Modeling Parameters and Their Impact on Modelled Permafrost Responses to Climate Warming

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Abstract

Rapid climate warming is causing permafrost degradation in the Arctic, which negatively impacts infrastructure stability. A deeper harmonic active layer has been observed as a result of progressive permafrost thawing due to climate change. In this study, critical parameters were assessed using CMIP5 and TEMP/W software to examine how permafrost ground responds to climate warming. We modelled active layer thickness (ALT) and future settlement and examined the sensitivity of these parameters to change model depth, climate scenarios, water content, and soil types. We found that for all soil types, the amount of water has the strongest influence on the time and depth at which permafrost thaws, where lower water content results in larger changes in active layer and more settlement.

Study Sites

Figure 1: The study area showing the Hudson Bay Railway extending from Churchill to The Pas, Manitoba.

Water Content Sensitivity Analysis

This study presents a sensitivity analysis aimed at evaluating the impact of water content on ALT and settlement for different soil types. To this end, water content values of 0.1, 0.3, 0.5, 0.7 and 0.9 were selected as input parameters.

Observations of Water Content Sensitivity Analysis:

- Significant influence on ALT changes and settlement observed in all simulations.
- Magnitude of settlement ranges from 5 to 60 cm, depending on soil and permafrost region.
- Higher water content generally leads to smaller ALT changes and cumulative settlements due to latent heat and ice's higher heat capacity.
- Clay soils exhibit higher thaw strain on average compared to other soil types.

Key Findings:

- Soil type, especially clay content, plasticity, and expansiveness, influences ALT changes and settlement magnitude.
- Specific soil characteristics must be considered for accurate assessment of ALT changes and settlement, emphasizing the importance of understanding soil behavior in freeze-thaw conditions.

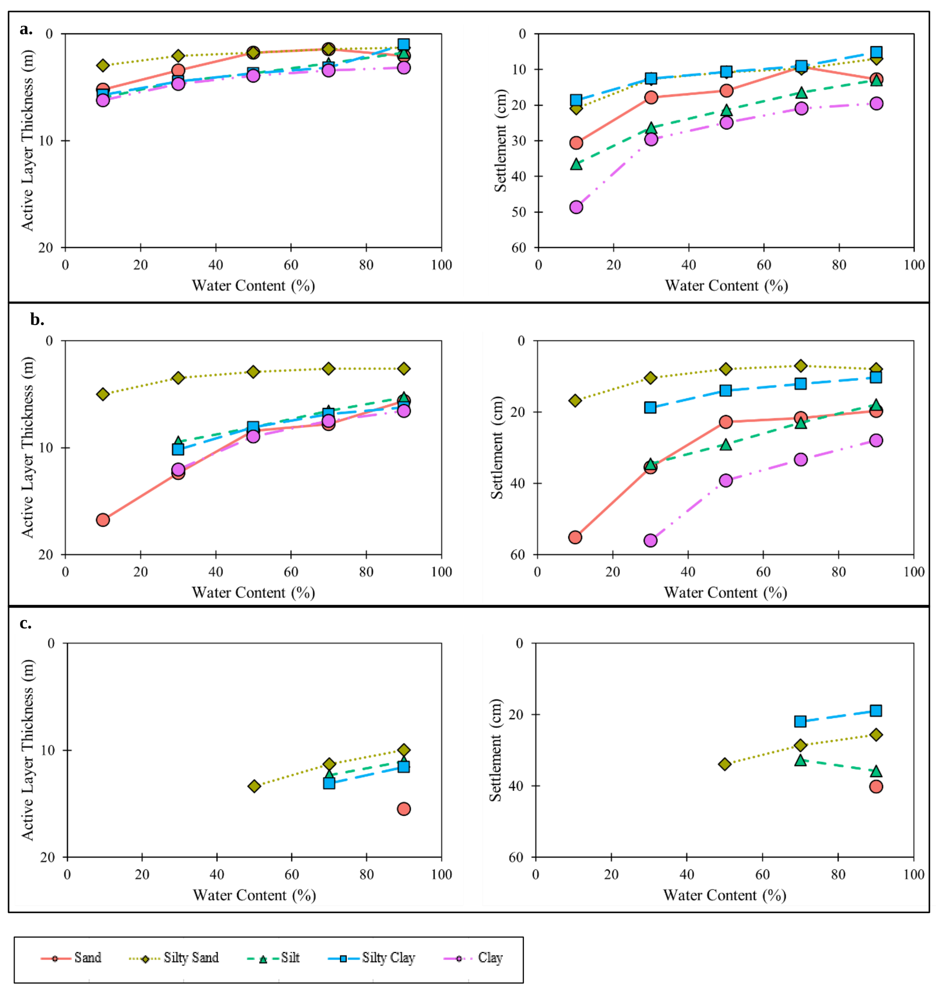

Figure 2: ALT and settlement results for different water contents in a. continuous, b. extensive discontinuous and c. sporadic discontinuous permafrost regions along the Hudson Bay Railway in 2070 under RCP 8.5 climate scenario.

Depth of Model Sensitivity Analysis

A sensitivity analysis was conducted to determine how model depth affects ALT and settlement. Simulations with soil columns of 15, 20, 30, 40, and 50m depth were compared.

Key Influence of Depth of Model Sensitivity Analysis:

- Higher water content reduces susceptibility to changes in model depth as water enhances thermal conductivity, facilitating efficient heat transfer and dissipation.
- Lower water content, like 30%, increases sensitivity to model depth changes, affecting ALT and settlement as water content limits soil's heat transfer and thermal buffering capacity, intensifying sensitivity to model depth changes.

Graphs Indication:

- ALT changes and settlement exhibit consistency across different simulation depths.

Key Findings:

- Clay soils show the greatest variability in ALT and settlement.
- Silty soils in continuous permafrost regions are vulnerable to model depth changes.
- Model depth is not solely critical; consideration of water content alongside depth is crucial.
- Model depth adapted to >30m to ensure most changes occur at 15 and 20m depths, ensuring result consistency.

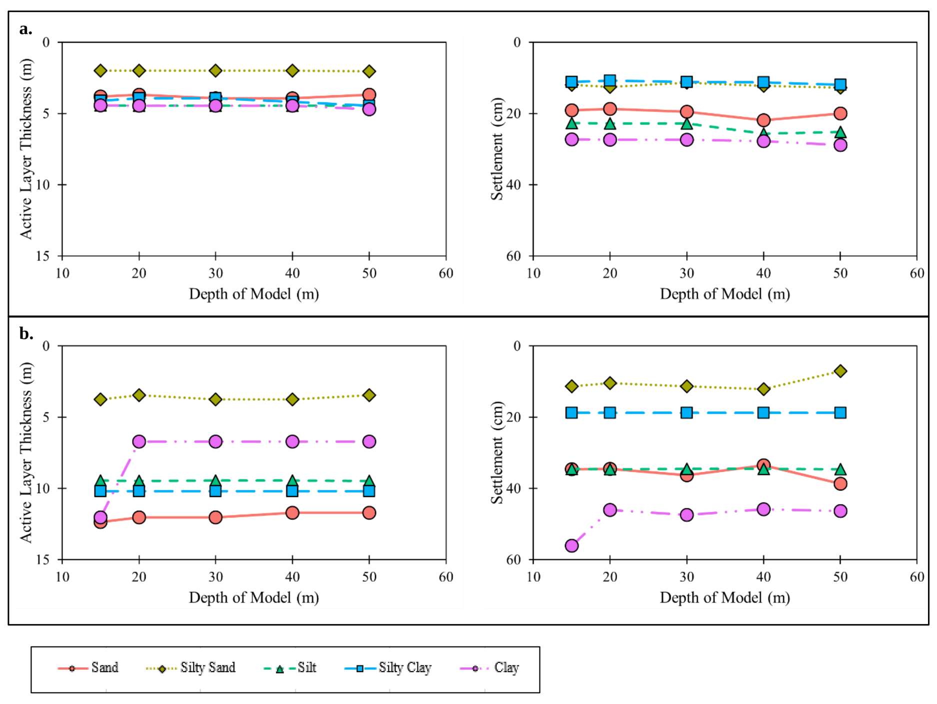

Figure 3: ALT and settlement results for different depth models and 30% water content in a. continuous and b. extensive discontinuous permafrost regions.

* Absence of points on graphs by 2070 indicates no permafrost presence.

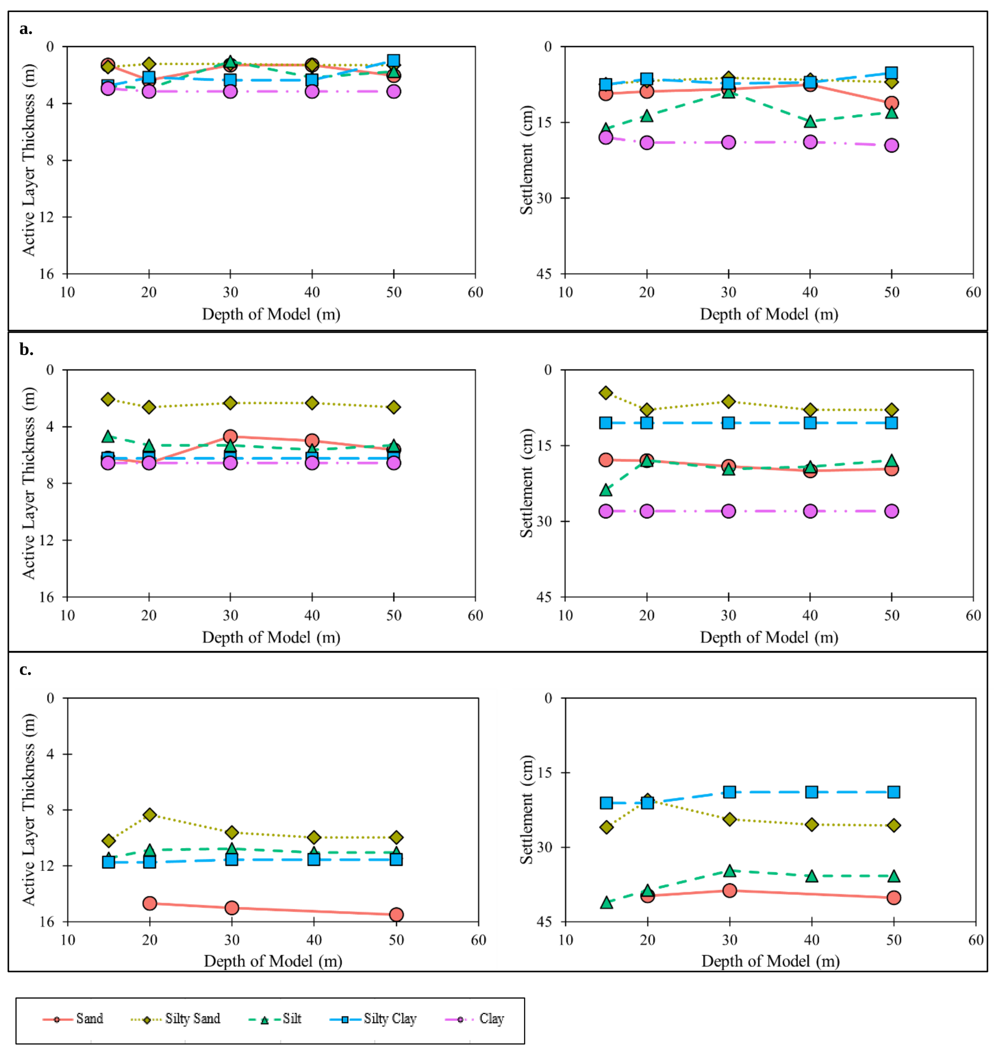

Figure 4: ALT and settlement results for different depth models and 90% water content in a. continuous, b. extensive discontinuous and c. sporadic discontinuous permafrost regions

Conclusion

- ALT and settlement are significantly influenced by permafrost coverage percentage.
- Greater permafrost coverage correlates with increased settlement by 2070.
- RCP8.5 predicts the highest settlement, but RCP4.5 occasionally shows extremes.
- Embankment settlement and thermal modeling are strongly influenced by water content.
- Higher water content in frozen ground leads to more ice and less sensitivity to climate warming.
- In thermal modeling, depth is not critical; its influence varies with soil water content.
- Model depth is a less critical parameter to soil samples with high water content values.

Future Work

- Probabilistic thermal analysis to determine thaw settlement probability distribution.
- Development of multiple equations for predicting thaw settlement in different soil types using probabilistic analysis.
- Thermo-mechanical simulations for a comprehensive understanding of thaw settlement, considering consolidation processes and soil mechanical response.