

Exploring the Influence of Surface Boundary Conditions on Thermal Regimes Beneath Flexible Pavements

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Abstract: The performance and durability of flexible pavements are intricately linked to their thermal regime, especially critical during spring thaw when weakened subgrades require load restrictions. This study meticulously evaluates the effectiveness of different pavement surface boundary conditions in predicting subsurface temperatures, utilizing a sophisticated numerical model incorporating an unsaturated soils framework. Three methodologies are examined: traditional empirical methods, the n -factor approach (surface-to-air temperature index ratio), and a surface energy balance (SEB) boundary condition. Extensive analyses consider climatic conditions and the subgrade properties with changing thermal properties along depth. Results reveal a significant dependence of the thermal profile on the chosen boundary condition, alongside the impact of climatic dynamics and subgrade characteristics on temperature prediction with disparities among the studied methods. While simpler approaches relying on limited factors fail to capture the complete site information, SEB offers a more accurate comparison by incorporating a wider range of parameters. This study highlights the importance of appropriate boundary condition selection to precisely estimate the maximum frost depth, facilitating better engineering design for roads, bridges, and building foundations as well as informed decision regarding utility line placement to prevent future damage.

Introduction

Asphalt pavements are a crucial component of transportation systems, providing essential infrastructure for mobility. The structural strength, performance and longevity of asphalt layers are significantly influenced by temperature variation. These variations result in freeze-thaw cycles, which induce fatigue processes in the pavements, ultimately causing cracking and degradation over time. Consequently, it becomes essential to accurately predict subsurface temperatures and frost depths (FD) for understanding and mitigating the thermal impacts on pavement performance. Several methods exist for predicting maximum FD, broadly categorized as empirical and numerical approaches. In general, empirical relationships are used to estimate the freezing depths. While these models are simple, they are site specific and may not be applicable across various regions. On the other hand, the numerical models simulate heat flow using the Fourier law, incorporating phase change and moisture transport, making them more

reliable. However, numerical models require accurate boundary condition at pavement-air interface to achieve reliable maximum FD predictions. Despite the availability of advanced numerical tools, the impact of varying pavement surface boundary conditions on thermal predictions remains inadequately explored. Pavement temperatures, which differ from air temperatures, serves as a key input. Various empirical models have been developed to estimate pavement temperatures from air temperature including n -factor approach, SHRP, and C-SHRP methods. [1-5].

This research investigates the critical role of the top boundary condition in thermal numerical modeling for accurate FD prediction in pavement systems. A key challenge in modeling subsurface thermal behavior is defining appropriate surface thermal boundary conditions. Although numerous methods exist for estimating pavement temperature from air temperature, a standardized approach for integrating these estimates into geotechnical thermal models is lacking [6]. This study addresses this gap by systematically evaluating various top boundary condition approaches for predicting subsurface temperatures and maximum FD. Specifically, FD predictions derived from models using pavement temperatures estimated via established empirical methods are compared with those obtained using a surface energy balance (SEB) technique. The SEB approach is implemented as a system-dependent boundary condition, predicting surface temperature dynamically through climate interaction. Model results are validated against field data to determine the efficacy of each boundary condition approach.

Pavement Surface Temperature Models

Various empirical approaches have been developed for predicting pavement and surface temperatures under varying climatic conditions. The empirical approaches estimate surface temperature by applying adjustments to the air temperature. Some of the widely used models to estimate pavement temperature from air temperature are presented below which are employed in this study.

The n -factor approach which utilizes a simple multiplication with a factor which is a ratio of surface thawing or freezing index to that of air [1,2] and is given by equations 1 and 2. Typical freezing and thawing n -factors values for asphalt, reported in literature, range from 0.8 to 0.95 and 1.6 to 3, respectively [1,2].

$$T_{s(max)} = n_t \cdot T_{a(max)} \quad (1)$$

$$T_{s(min)} = n_f \cdot T_{a(min)} \quad (2)$$

Where $T_{s(max)}$ and $T_{s(min)}$ are maximum and minimum pavement temperatures at the surface ($^{\circ}\text{C}$), $T_{a(max)}$ and $T_{a(min)}$ are maximum and minimum air temperatures ($^{\circ}\text{C}$), n_f and n_t are freezing and thawing n -factors.

The Strategic Highway Research Program (SHRP) proposed adjustment to the pavement temperature by utilizing the factors such as latitude and depth from pavement surface while Canadian SHRP (C-SHRP) recommends an additional scaling factor, utilizing a dataset from

Canadian sites. The original SHRP models for estimating high and low pavement temperatures were developed by Solaimanian and Bolzan (1993) [7]. The current SHRP models used in selection of asphalt binder performance grading (PG) are given through equations 3-5. Equation 3 yields the high pavement temperature at the surface, equation 4 and 5 expresses high and low pavement temperature at any depth, d respectively:

$$T_{s(max)} = T_{a(max)} - 0.00618 Lat^2 + 0.2289 Lat + 24.4 \quad (3)$$

$$T_{pav(max)} = [T_{s(max)} + 17.8] [1 - 2.48 \times 10^{-3} d + 1.085 \times 10^{-5} d^2 - 2.441 \times 10^{-8} d^3] - 17.8 \quad (4)$$

$$T_{pav(min)} = T_{a(min)} + 0.051 d - 0.000063 d^2 \quad (5)$$

Where $T_{s(max)}$ is maximum pavement temperature at the surface ($^{\circ}\text{C}$), $T_{a(max)}$ is maximum air temperature ($^{\circ}\text{C}$), and Lat is latitude in degrees, $T_{pav(max)}$ is highest pavement temperature at any depth below the surface ($^{\circ}\text{C}$), d is depth in mm, and $T_{pav(min)}$ is minimum pavement temperature at any depth below the surface ($^{\circ}\text{C}$).

The high temperature prediction for C-SHRP remains same as SHRP while the low temperature model variation with depth is updated by Robertson using low-temperature data from Canadian sites (equation 6): [3]

$$T_{pav(min)} = 0.859 T_{a(min)} + (0.002 - 0.0007 T_{a(min)})d + 0.17 \quad (6)$$

While SHRP's contribution, such as Superpave system, have significantly advanced pavement design, the accurate incorporation of thermal boundary conditions into geotechnical applications remain a key unresolved issue.

Field Measurements

The Ministry of Transportation Ontario (MTO) operates several Spring Load Adjustment (SLA) stations across Northern Ontario, Canada. These stations monitor climatic and subsurface conditions using an array of sensors. Recorded data includes air temperature, relative humidity, pavement temperature, subsurface temperatures (at depths of 15, 30, 45, 75, 90, 105, 135, 165, 195, 225, and 255 cm), and soil volumetric water content (at depths of 15, 45, and 100 cm).

This research primarily aims to determine surface temperature from ambient temperature using empirical and numerical approaches at Spring Load Adjustment (SLA) station 599 in Northern Ontario (location shown in Figure 1). These derived surface temperatures are then incorporated as boundary conditions in a thermal model to determine the most accurate approach for evaluating FD trends and maximum FD.

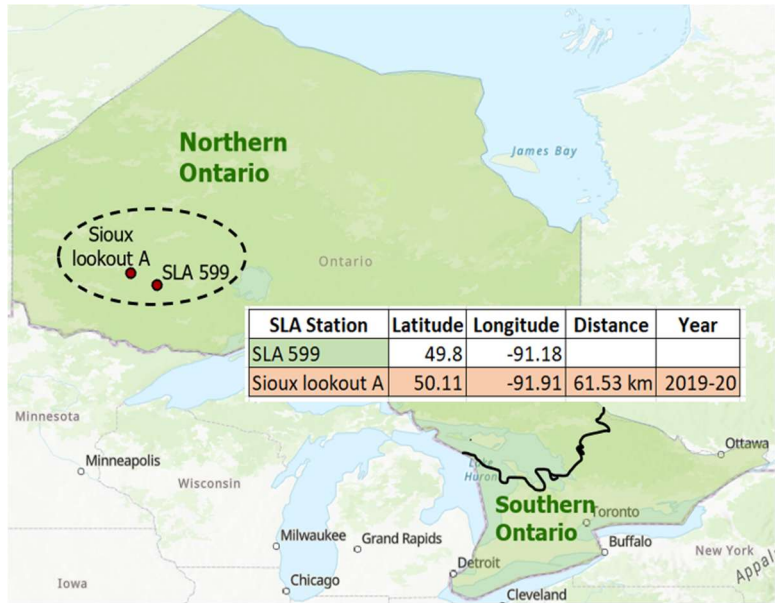


Figure 1: Location Map

The maximum FD was predicted (interpolated between two points) based on the variation in subsurface temperature with depth as shown in figure 2. Three empirical methods – *n*-factor, SHRP, and C-SHRP were applied to estimate surface temperatures from ambient air data. Additionally, the SEB approach was implemented in numerical modelling using climate data for the above-mentioned site. The performance of these models was then evaluated by comparing the subsurface measured temperature data collected at the site.

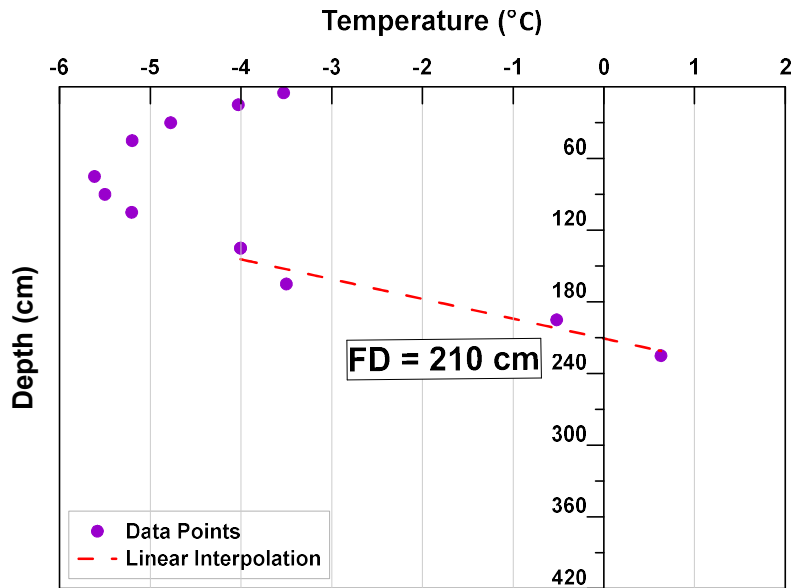


Figure 2: Maximum Interpolated Frost Depth (SLA 599, 2019-2020)

Development of Numerical Model

In this study the numerical modelling was carried out using TEMP/W which is a software package by Geo-Slope international [8]. The thermal analysis involves three key components: geometry, material properties and boundary conditions. Temp/W offers a range of thermal and material modeling options; therefore, the impact of various pavement surface boundary conditions on the prediction of subsurface temperatures and FD was evaluated.

A one-dimensional numerical model was developed for SLA 599 with a total depth of 30 m. The model comprises of four layers: an asphalt layer with a thickness of 25 mm, a base layer of 300 mm, a subbase layer of 775 mm, and an underlying subgrade soil. The subgrade predominantly consists of sand, with varying fractions of gravel and silt. The characteristics and thickness of the layers correspond to field investigations conducted at the study location.

The thermal model incorporated boundary conditions along with the unsaturated material properties, including in-situ volumetric water content (VWC), bulk thermal conductivity, and bulk volumetric heat capacity for the pavement layer, granular base, and subgrade. An SEB approach was implemented for both full thermal and simplified thermal models. In TEMP/W, simplified thermal models treat pore water as either fully frozen or unfrozen, applying latent heat instantaneously at a single temperature. Full thermal models, conversely, simulate a gradual phase change over a temperature range, distributing latent heat absorption or release more realistically. This approach enables full thermal model to more accurately represent the coupled thermal and moisture behaviour in unsaturated soils. This difference in treatment of latent heat is the fundamental distinction between the two model approaches.

The model required input data including air temperature, relative humidity, solar radiation, and wind speed. Temperature and humidity data for the SLA site were available, while solar radiation values were estimated using a user-defined function in TEMP/W that accounts for latitude. Since the wind speed data for SLA Station 599 was unavailable, values from the nearest weather station, Sioux Lookout A, were used instead. The location of this weather station and its proximity to SLA Station 599 are shown in Figure 1.

Material properties

The bulk volumetric heat capacities and thermal conductivities for the base, and subgrade materials were measured in the lab using KD-2 Pro with dual sensor SH-1 at various dry density and moisture content values. The bulk thermal conductivity and bulk volumetric heat capacity value for the asphalt layer are consistent with those reported by Luca and Mrawira (2005),[9]. The calculated material input parameters for the numerical model are summarized in Table 1.

Table 1: Summary of input parameters

<i>Material Type</i>	<i>Layer Depth(m)</i>	<i>Volumetric Water Content</i>	<i>Thermal Conductivity (KJ/sec. m. °C)</i>		<i>Volumetric Heat Capacity (KJ/m³. °C)</i>	
			<i>Frozen</i>	<i>Unfrozen</i>	<i>Frozen</i>	<i>Unfrozen</i>
Asphalt	0.025	0	0.0014	0.0014	1575	1575
Base	0.475	0.064	0.0011	0.00155	1423	1576
Subbase	0.3	0.055	0.00119	0.00167	1476	1611
Subbase	0.4	0.0461	0.00089	0.00138	1381	1492
Subgrade	≥ 1.2	0.0461	0.00077	0.00124	1335	1437

Boundary Conditions

The validation model was conducted in two stages: a steady-state analysis followed by a transient analysis. The steady state analysis was performed to establish thermal equilibrium within the soil, serving as initial condition for the first day of transient analysis. For the steady state analysis, the top boundary condition was set to the average annual temperature, while a constant unit heat flux of 4.232×10^{-5} KJ/s. m², representing the geothermal gradient, was applied at the bottom boundary. The bottom boundary was placed at 30 m depth, where the soil temperature remains constant year-round and is unaffected by seasonal climate change. Prior to conducting the transient analysis for a target year, a 10-year spin-up simulation was performed using data from the previous year. This approach ensured that the model is not influenced by the initial conditions.

In the transient analysis, the pavement surface boundary conditions were derived using *n*-factor, SHRP, and C-SHRP pavement temperature models (Eqs. 1-6). For the *n*-factor model, site-specific freezing and thawing *n* factors 0.8 and 1.6, respectively, were employed. These values were chosen from the recommended range of values by Dore and Zubeck [2].

Additionally, the SEB approach was employed which determines surface temperature through energy balance calculations, incorporating climatic parameters an energy transport within the modeling domain. This domain treats surface temperature as a system-dependent boundary condition, derived as a part of solution. SEB was employed for both full and simplified thermal models, utilizing variations in air temperature, relative humidity and wind speed over time. A constant albedo of 0.15 was used, consistent with values commonly found in the literature and recommended by previous studies [10, 11].

Results and Discussion

This section presents and discusses the findings of this study. First, the results of pavement surface temperature predictions from empirical models are compared with actual field

measurement. Results of numerical model with different top boundary conditions are then evaluated against field measured values.

The predicted surface temperatures at 5 cm depth, obtained using the three-pavement surface models were assessed through the statistical analysis, presented in Figure 3 in the form of a box and whisker plot. The SHRP and C-SHRP models over predicted the soil temperature during the summer, with deviations ranging from 3 °C to 20 °C. The *n*-factor alternative provided a lower variation in predicting the soil temperature below the pavement surface, with maximum variation of ±10 °C, attributed to the use of calibrated freezing and thawing factors. For freezing months, all the models exhibited minimal variation in temperature predictions, indicating better agreement with field data under these conditions.

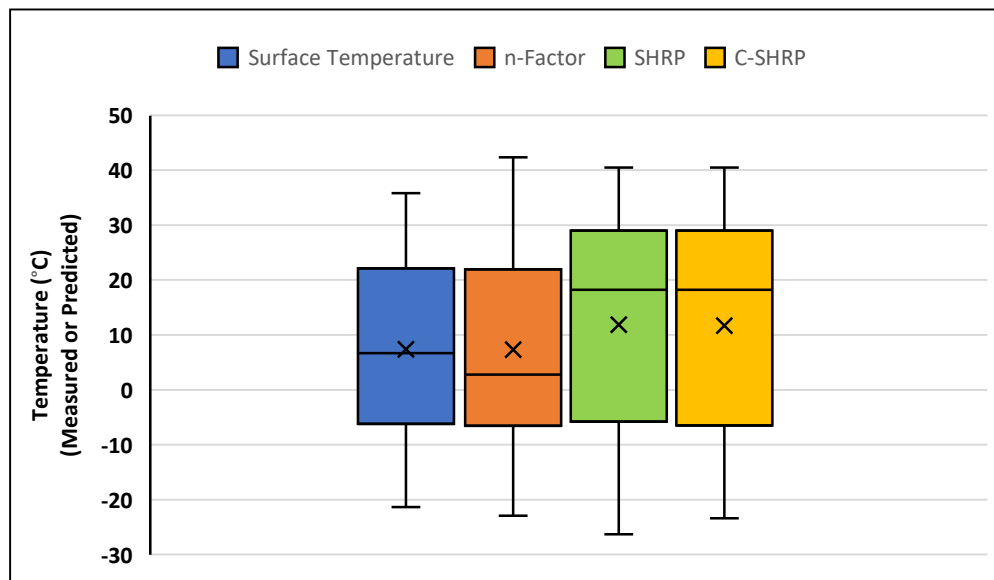


Figure 3: Variation in data between measured and predicted Surface temperature at 5 cm using *n*-Factor, SHRP, and C-SHRP

The coefficient of determination (R^2) values for *n*-factor, SHRP, and C-SHRP obtained through linear regression of measured and predicted pavement temperatures at 5 cm depth are presented in figure 4. The SHRP and C-SHRP models exhibited similar values, indicating comparable performance particularly during freezing months. These two models although rely on the measured air temperature data, but their predictions are primarily function of only latitude and distance from the pavement surface, limiting their accuracy. The *n*-factor approach achieved slightly better results, but this was due to the site-specific calibration, requiring precise n_f and n_t values tailored to the specific location, which might not work for any other site.

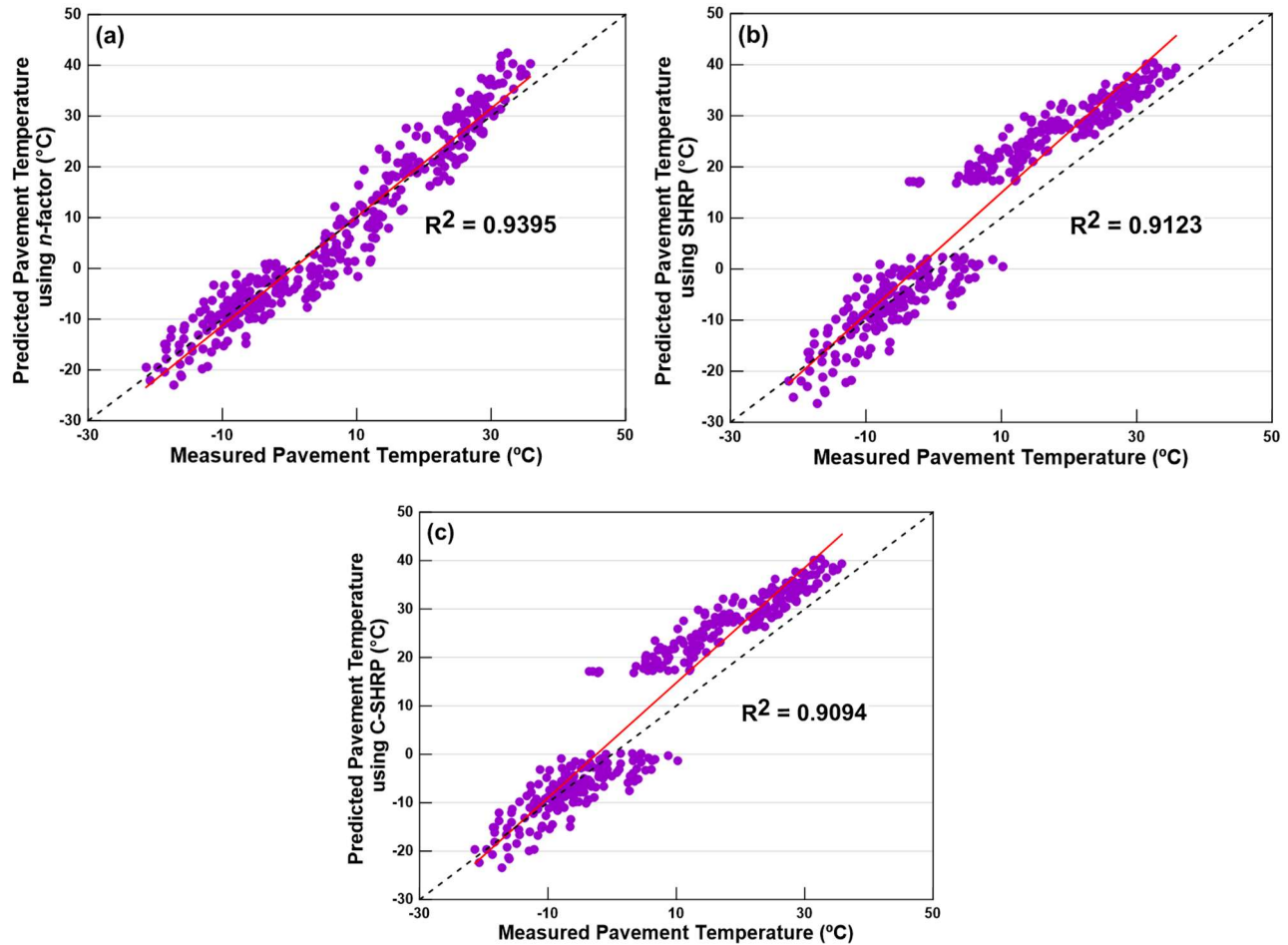


Figure 4: Variation in data between measured and predicted Surface temperature at 5 cm using a)- n -Factor, b)- SHRP, and c)- C-SHRP

The predicted soil temperatures using the three empirical pavement temperature boundary conditions and the SEB boundary condition are compared to field-measured values in Figure 5. For the SEB boundary condition, results from both the simplified and full thermal models are presented.

Figure 5 shows that the model using the SEB approach with the full thermal model not only captures the freezing trend over time but also predicts the maximum FD with high accuracy. Additionally, the model employing the SEB approach with the simplified thermal model also produces acceptable results. The model using the boundary condition predicted by the n -factor approach provides reasonable results as well. However, it should be noted that these results were achieved by calibrating the n -values, as the literature reports a range of values for asphalt: freezing (n_f) values between 0.8 and 0.95, and thawing (n_t) values between 1.6 and 3. In contrast, numerical models using top temperature boundary conditions derived from SHRP and C-SHRP show significantly poorer performance, underpredicting the maximum FD by as much as 40–45 cm.

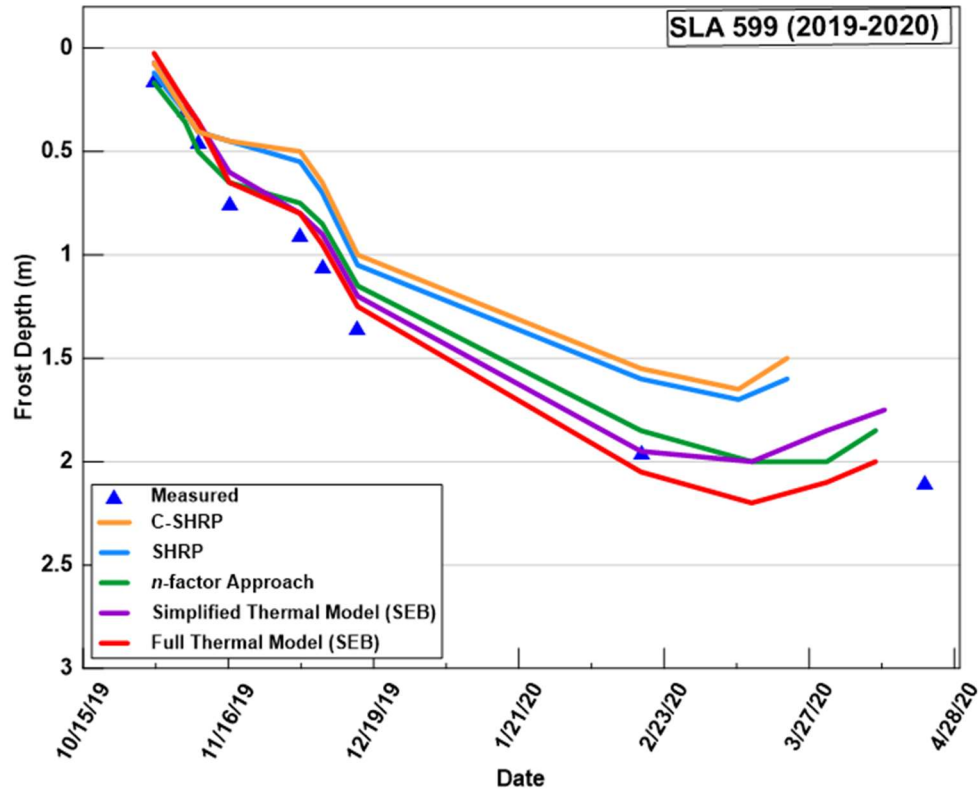


Figure 5: TEMP/W model Validation (Trend Analysis) SLA 599

Conclusions

1. The empirical methods evaluated in this research exhibit variability in their ability to predict pavement surface temperatures.
2. The use of different boundary conditions in numerical models can lead to variation in maximum FD estimates with discrepancy of up to 45 cm.
3. The surface energy balance approach provides the most accurate estimate of maximum frost depth and captures its variation trend with depth and time reasonably well.
4. Results also suggest that full thermal model improves prediction capability compared to simplified thermal model because of its capability of capturing complex relationship between temperature, water content and latent heat transfer during phase change in an unsaturated soil.
5. Although surface energy balance approach closely aligns with the measured values, it requires additional climate data and computational resources.

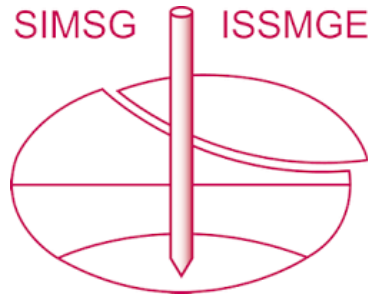
Accurate prediction of maximum frost depth utilizing a suitable surface boundary condition is essential for optimizing the structural design of pavements, bridges, building foundations and underground utilities. The SEB approach when applied with full thermal model, exhibited enhanced estimation accuracy. Its integration of unsaturated soil behaviour presents opportunities for further research. Future work will focus on expanding the application of full

thermal modeling to a wider range of unsaturated soil types, including silts and clays, to better understand the thermal response under different moisture and climatic regimes. Investigating the impact of dynamic saturation levels and seasonal water content variations on frost depth will further improve the accuracy and applicability of thermal models in real-world geotechnical scenarios. These advancements will contribute to more resilient and cost-effective infrastructure design in cold regions.

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