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Abstract

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Disciplines

Agronomy and Crop Sciences | Mechanics of Materials | Transportation Engineering

Comments

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Predicting Soil Temperature and Moisture beneath Granular-Surfaced Roadways using Regional Weather Data Network

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ABSTRACT

The performance of granular-surfaced roadways is greatly affected by annual freeze-thaw cycles, which can cause severe structural damage to the road surface. The collection of in-situ subgrade soil temperature and moisture data as well as local weather data is very important to improve our ability to understand and predict subgrade behavior during freeze-thaw cycles. In this study, the use of data from a weather station installed adjacent to a granular road test section is compared to data interpolated from the two nearest weather stations of a statewide network, to compare their performance as inputs for freeze-thaw simulations using the Simultaneous Heat and Water (SHAW) model. The subgrade temperature and moisture content predictions from the simulations are compared to those measured by sensors installed at several depths below the soil surface at the center of the test section. The results suggest that using weather input data from the statewide weather station network may result in reasonably accurate predictions from SHAW simulations.

INTRODUCTION

Granular-surfaced roadways in seasonally cold regions are adversely affected by annual freeze-thaw cycles. The mechanical properties of the roadway can degrade, causing severe structural damage during spring thawing (Shoop et al. 2008). For this reason, it is important to understand the freeze-thaw mechanisms and associated moisture transport beneath granular roadways. Enhanced understanding of these processes can improve freeze-thaw predictions, and consequently, improve the scheduling of maintenance operations and the resulting roadway performance (Lein et al. 2019). Environmental factors such as water availability and traffic loads affect the severity of freeze-thaw related damage and the engineering properties of the subgrade soil beneath roadways (White and Vennapusa 2013). Data on atmospheric conditions are necessary to fully characterize the boundary conditions of the roadway cross-section in terms of heat and water fluxes into the system.

Transportation and highway agencies have invested significant resources into weather monitoring systems for some time. They routinely collect and use meteorological information to help guide road maintenance and snow and ice control (Boselly et al. 1993). Road Weather Information System (RWIS) weather stations, with specialized information on road surface conditions, have been around for nearly 50 years (Zwahlen et al. 2003). The RWIS system consists of stations equipped with various sensors to obtain continuous information on weather metrics and road conditions (Vavrik et al. 2016). According to a survey of 24 states in the U.S., 35% of the Departments of Transportation (DOTs) expect to spend between 1% and 10% of their annual funding on RWIS systems, while 45% of DOTs anticipate spending more than 10% (Ewan and Al-Kaisy 2017). As the availability and quality of weather monitoring stations increase, the accuracy of freeze-thaw predictions from computational models should also increase.

In this study, the accuracy and usability of weather station data from two statewide networks are evaluated in terms of predictions of freeze-thaw behavior beneath a granular-surfaced roadway. The Simultaneous Heat and Water (SHAW) model was used to predict the temperature and moisture conditions of an instrumented subgrade underlying a granular-surfaced road test section in Iowa, using the weather data as inputs. Data from a weather station installed at the test site was also used in modeling to assess the accuracy of using input data from nearby stations of the statewide network.

TEST SECTION AND IN-SITU DATA COLLECTION

For the test section, a north-south granular-surfaced roadway was selected in Hamilton County, Iowa. The subgrade of the road at the centerline was instrumented with MPS6 and GS-1 sensors (manufactured by Meter Environment) for measuring soil water potential and temperature, and volumetric water content, respectively. The sensors were installed at depths ranging from 0.15 to 2.13 m below the bottom of the aggregate layer (Figure 1). A composite type weather station (Meter Environment ATMOS 41) was also installed 4.6 m above the ground surface in the west ditch of the roadway. The weather station measured local atmospheric data including precipitation, air temperature, relative humidity, solar radiation, and wind speed, which were all recorded simultaneously with the data from the soil sensors.

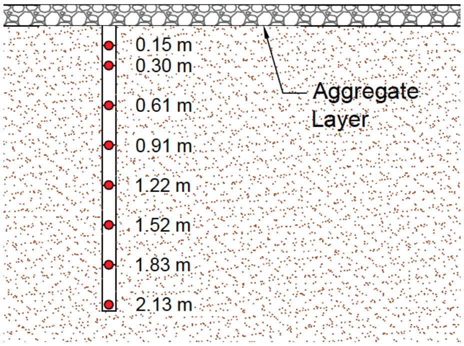

Figure 1. Cross-section of the granular-surfaced roadway showing depths of sensors beneath soil surface.

The data acquisition system was programmed to collect data from the sensors and weather station at 10-minute intervals to be consistent with the RWIS network, which is the weather and pavement monitoring network generally used for road applications for operations and maintenance (Manfredi et al. 2008). The Iowa RWIS network consists of 86 stations (Iowa Environmental Mesonet 2020a). However, RWIS data on precipitation, relative humidity and solar radiation were not available from the Iowa Environmental Mesonet (IEM) archive. Therefore, the Iowa State University Soil Moisture Network (ISU SM), which is a similar statewide network of observation stations, was used to obtain the necessary atmospheric data for input to the SHAW computational simulations. The ISU SM Network is one of several available on the IEM archive which collects continuous daily or hourly atmospheric and soil measurements. The network consists of a total of 26 stations, which are primarily located at Research and Demonstration Farms (Iowa Environmental Mesonet 2020b). The stations were formed using Campbell Scientific sensor packages. A list of the sensors and their ranges and resolutions are given in Table 1 for both the ISU SM Network and the ATMOS 41 weather station (Iowa Environmental Mesonet 2020c; Meter Environment 2017).

Table 1: Sensor names and properties for the weather stations used in this study.

Station	Sensor type	Measurement Range	Measurement Resolution
ISU SM	Air Temperature	-40 to 70 °C	0.01 °C
ISU SM	Precipitation	15.4 cm orifice diameter	0.254 mm
ISU SM	Relative Humidity	0 to 100 %	0.03 %
ISU SM	Solar Radiation	0 to 2,000 W/m^2	≈0.0003 W/m^2*
ISU SM	Wind Speed	0 to 50 m/s	≈0.0004 m/s*
ATMOS 41	Air Temperature	-50 to 60 °C	0.1 °C
ATMOS 41	Precipitation	9.31 mm orifice diameter	0.017 mm
ATMOS 41	Relative Humidity	0 to 100 %	0.1 %
ATMOS 41	Solar Radiation	0 to 1,750 W/m^2	1 W/m^2
ATMOS 41	Wind Speed	0 to 30 m/s	0.01 m/s

*estimated from downloaded data.

The two ISU SM stations closest to the test section were identified and selected for the modeling phase. These stations are named Ames (AEEI4) and Kanawha (KNAI4), and are located 17 and 41 miles away, respectively, from the Hamilton County test section (Figure 2). Thus, the modeling results will represent a comparison of the soil profile predictions using atmospheric data inputs measured 0, 17 and 41 miles from the test site.

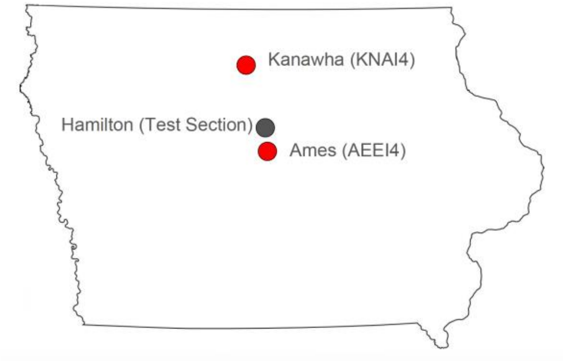

Figure 2. Locations of test section and selected ISU SM stations; Kanawha (KNAI4) and Ames (AEEI4).

FREEZE-THAW BEHAVIOR SIMULATION WITH THE SHAW MODEL

The SHAW model is a comprehensive computational program originally developed to simulate freeze-thaw behavior of soil within a predetermined time period using atmospheric data as input. It also simulates simultaneous heat, water and solute transfer within a vertical, one-dimensional soil profile consisting of several layers (Flerchinger 2017). The simulations are capable of including the effects of plant cover, snow, and crop residue, but these effects were neglected in the present study due to a lack of input data.

The model defines soil layers using their physical properties including particle size distribution, bulk density, saturated volumetric water content, and saturated hydraulic conductivity, which are input by the user. The initial temperature and water content values are also required to define the initial soil conditions. The external atmospheric inputs affect the thermal and hydraulic conditions of the soil layers. Therefore, use of the three different weather stations shown in Figure 2 for the atmospheric inputs to SHAW were expected to give different results.

In the SHAW model, the water and heat fluxes are determined at nodes located at the middle of each layer according to the user-specified initial profiles and boundary conditions. In order to directly compare the in-situ temperature and water content measurements of the sensors to the simulation results, the soil layers were defined such that the sensor locations coincided with the layer nodes. The resulting 11-layer soil profile is shown in Figure 3.

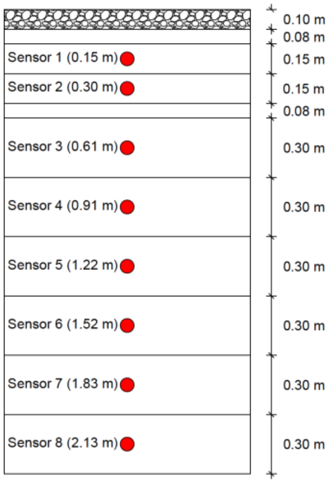

Figure 3. Soil profile defined in the SHAW model for the Hamilton County test section.

The soil property inputs for each layer were obtained from extensive laboratory tests performed on Shelby tube samples collected during installation of the sensors. The samples contained the subgrade material from near the instrumented center location to a depth of 2.13 m below the aggregate layer. The soil samples were divided into 0.30-m long segments for laboratory tests. Sieve analysis and hydrometer tests were performed to determine the particle size distribution (ASTM D6913, D7928), and constant head permeability tests (ASTM D2434) were performed using a modified high-pressure Shelby tube permeameter to measure saturated hydraulic conductivity. However, the lab tests were performed before SHAW modeling was initiated, and the subdivided 0.30-m long soil segments in the lab were not fully consistent with the soil layers centered on the sensors in the SHAW model (Figure 3). Therefore, the layers in the model were represented either by using the laboratory results directly if the laboratory soil segment was within the modeled layer, or by averaging the results of two segments nearest the depth of the node.

The atmospheric data from the ISU SM stations used a sampling interval of one hour. However, the local in-situ weather station was programmed to record data at a shorter sampling interval of 10 minutes. The in-situ weather station data of the 60 minutes after the hourly timestamp were therefore averaged to obtain hourly values for consistency with the ISU SM stations. For this study, the selected simulation period was September 15, 2019 to March 13, 2020. Finally, the aggregate layer of the granular road was modeled as another soil layer on top of the subgrade layers, and assigned aggregate layer properties obtained from laboratory tests. The weather data recorded from the local in-situ weather station and the two ISU SM network stations shown in Figure 2 were then used as inputs for separate SHAW analyses for comparison purposes.

RESULTS AND DISCUSSION

The SHAW model calculated the dynamic temperatures and volumetric water contents at the soil nodes using the entered subgrade layer properties and the time-dependent atmospheric data from the three different weather stations. From the in-situ water content observations, the groundwater level varies around 1.20 m below the bottom of the aggregate layer. The simulation results are obtained for all nodes shown in Figure 3, which coincide with the sensor locations. However, only two representative depths are shown herein due to space limitations. The datasets from the sensors at 0.15 m and 1.83 m, shown in Figures 4 and 5, are representative of one depth above and one depth below the average water table depth.

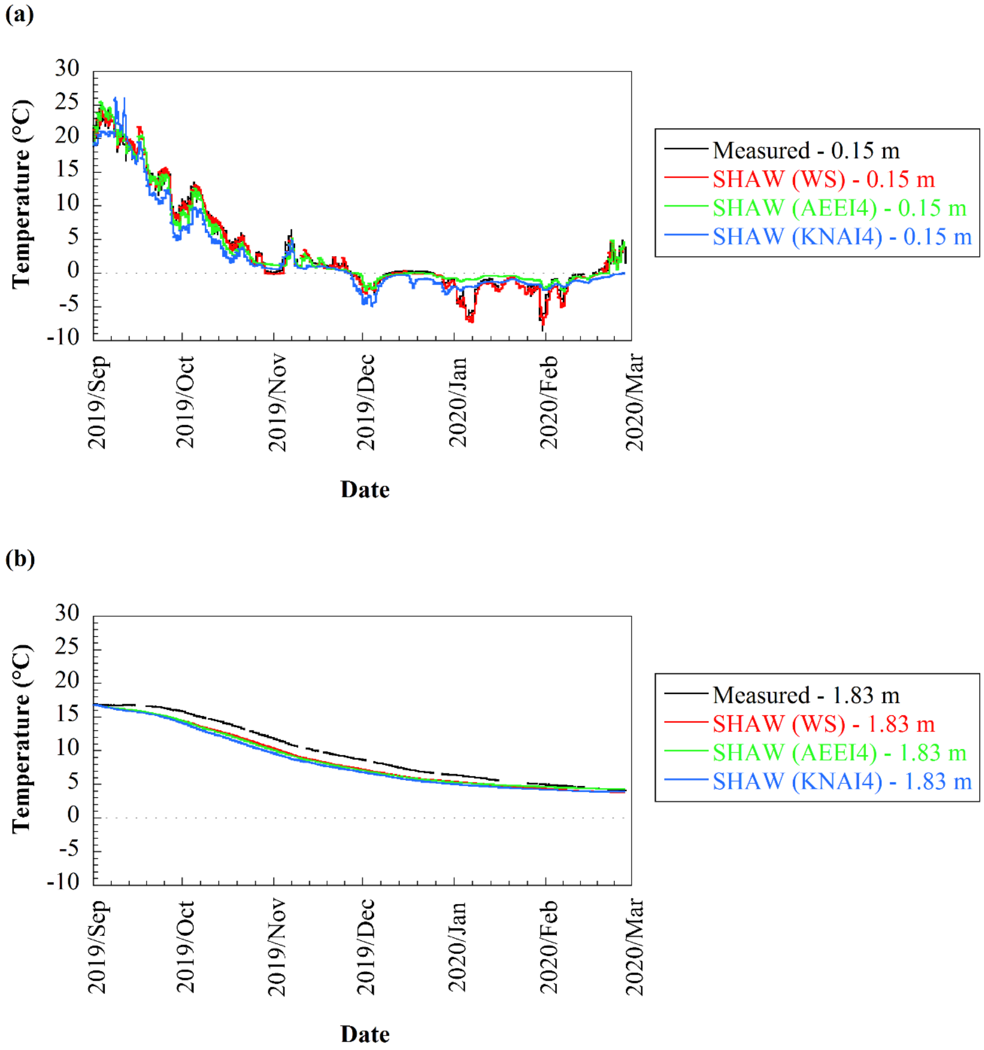

Figure 4. Comparison of in-situ measured temperature values and SHAW model simulation results for different weather station inputs for depths of (a) 0.15 m and (b) 1.83 m. (WS=local weather station at project site)

The temperature simulation results indicated that the ISU SM weather stations were useful for predicting the general trends of soil temperature at shallower depths, as seen for the sensor at 0.15 m. However, their values were not accurate enough to predict the sudden temperature drops that were captured by the in-situ weather station in early January and February. Neither the Ames

(AEEI4) nor Kanawha (KNAI4) weather input data were able to replicate the temperature drop of almost 5°C (Figure 4a), but this drop was accurately captured using the local weather station data as input to the model. However, these discrepancies decreased and nearly disappeared at greater depths. For example, the simulation results from all three weather stations were very consistent, although they all underestimated the field temperature by almost 2°C (Figure 4b).

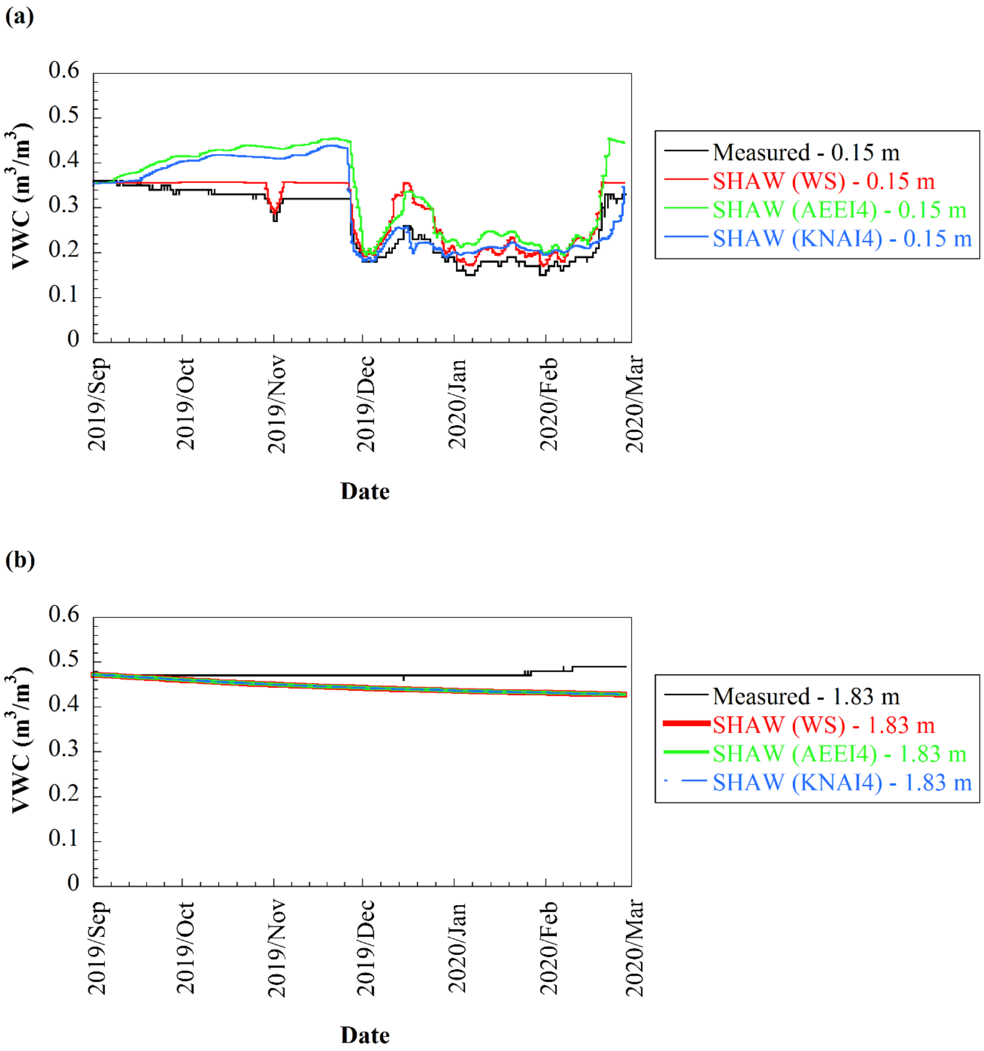

Figure 5. Comparison of in-situ measured volumetric water content (VWC) values and SHAW model simulation results for different weather station inputs for depths of (a) 0.15 m and (b) 1.83 m. (WS=local weather station at project site)

The SHAW simulation results for volumetric water content (VWC) produced findings similar to those of the temperature results, at both the shallow and deeper points. There is an obvious deviation in the simulated VWCs at 0.15 m depth for all three weather stations compared to the field measurements (Figure 5a). Both the Ames (AEEI4) and Kanawha (KNAI4) stations produced steady gradual increases in VWC right after the simulation began, whereas the local weather station's data produced a closer but not perfect match with the measured VWC. Yet, all three weather stations were able to closely match the field measurement at the first sudden drop in November at the onset of freezing. From that point until the end of the simulation, the values did not match but exhibited similar trends. However, as thawing progressed, the northernmost KNAI4 station was able to predict the thawing VWC trend better than the AEEI4 station south of the test site. During the month of December, the simulated VWC using input from the KNAI4 station was even closer to the measured VWC than that obtained using the local weather station. Similar to the temperature predictions, the discrepancies between the three water content simulations disappeared at deeper points. In fact, all three simulations converged to practically the same curves, which lie on top of each other in Figure 5b. The simulated VWCs at this depth also decreased slightly with time, whereas the measured values gradually increased.

In order to understand these differences better, the simulation errors were calculated by comparing the results with the field measurements. The normalized (dimensionless) errors were computed using each data point from the simulations and field measurements during the simulation period in Equation 1 to calculate the Coefficient of Variation (Root Mean Square Error):

$$CV\text{-}RMSE\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}}}{\bar{m}} \tag{1}$$

where m_i are the measured data values at a point in time, s_i are the corresponding simulation results, n is the total number of data points, and $\bar{m}$ is the average of all measured values.

Table 2: Coefficient of Variation error results for modeled temperature and volumetric water content at all depths for the three weather stations.

CV-RMSE (%)						
Depth (m)	**Temperature**			**VWC**		
	WS	**AEEI4**	**KNAI4**	**WS**	**AEEI4**	**KNAI4**
0.15	12	35	51	14	31	23
0.30	9	27	36	-	-	-
0.61	3	8	14	33	36	34
0.91	5	7	8	5	5	5
1.22	3	6	9	32	32	32
1.52	-	-	-	13	13	13
1.83	11	12	15	7	7	7
2.13	15	15	18	5	5	5
Average	8	16	22	16	18	17

The CV-RMSE could not be calculated at a few of the locations due to sensor malfunctions. The overall temperature and water content error values in Table 2 suggest that the model did capture both the temperature and water content dynamics beneath the road. However, the atmospheric data input from the three weather stations influenced the predicted temperatures more than the predicted water contents. For temperature, the errors are smallest at the middle of the instrumented soil profile. This could be because temperature fluctuations are larger and more frequent at shallower depths as they are more strongly influenced by the temperature and precipitation effects at the surface. Therefore, the simulations did not model the measured variations perfectly. The increasing temperature error at the deeper depths could be due to the assumptions of homogeneous soil layers, whereas the in-situ conditions are variable and non-homogeneous. Thus, the error between actual and modeled soil conditions may increase with depth. Nonetheless, the soil below the groundwater level reaches the saturated state and its temperature and water content do not change as much as above the groundwater level. As a result, the error between measured and simulated water content decreases with depth, since both are fixed at similar saturated values.

CONCLUSIONS

In this study, the SHAW model was used to simulate the freeze-thaw behavior for a vertical profile at the center of a granular-surfaced roadway in Hamilton County, Iowa. Three different sources of atmospheric data were used to understand the significance of weather inputs on freeze-thaw simulations where the soil properties were kept constant. The soil temperature and water content values from the simulations as well as in-situ measurements were compared visually and quantitatively. The effects of using data from different weather stations as inputs to the simulations were observed to be greater at the shallower depths, for both temperature and water content. However, the differences between simulation results diminished with increasing depth, whereas the variance between simulations and field measurements did not decrease. In addition, as CV-RMSE results suggested, SHAW was able to capture temperature more successfully than water content. In summary, using data from statewide weather station networks can be helpful for freeze-thaw prediction simulations, as it is not practical to have a local in-situ weather station at each site of interest. An agreement is observed between the measured and predicted profiles of temperature, moisture content, and freeze-thaw behavior, with the adjacent weather station’s data generating slightly better predictions than those generated from the more distant statewide weather stations. To improve the accuracy of simulations, the snow and plant cover variables neglected in this study can be included in the model in future studies. Finally, including the effects of traffic loads on the soil physical properties may be beneficial.

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