Environmental Impacts on the Performance of Pavement Foundation Layers-Phase I

MnDOT Project

Task 2 – Field Data Collection

August 31st, 2020
Revised October 6th, 2020

Prepared by:
Bora Cetin – Principal Investigator
Kristen Cetin - Co-Principal Investigator
Tuncer B. Edil – Co-Principal Investigator
Debrudra Mitra – Graduate Research Assistant

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. DATA DETAILS

In order to evaluate the occurrence of freeze thaw cycles and the resulting environmental impact on material performance, the research team measured and collected temperature and moisture data in the pavement structure over time at different depths at various locations and for different timespans. The research team setup an experimental data collection system to extract the material temperatures and moisture at six different locations. The test locations are distributed within a 2-mile span of roadway at the MNROAD facility at Monticello, Minnesota. Temperatures were measured at 12 different depths across each of these locations as shown in Table 1. Similarly, moisture content was also collected at four depths across these locations, as shown in Table 2. The measurements were collected at 15-minute intervals.

Table 1: Soil depths for measured temperatures

Cell no.	**Cell 185**	**Cell 186**	**Cell 188**	**Cell 189**	**Cell 127**	**Cell 728**
	Depth (in)					
TC_1	2.8	3	3	3	3	3
TC_2	3.8	4	4	4	4	4
TC_3	9.3	9.5	9.5	9.5	6.5	6.5
TC_4	14.8	15	15	15	9	9
TC_5	15.8	16	16	16	10	10
TC_6	18.3	18.5	18.5	18.5	12	14
TC_7	19.3	19.5	19.5	19.5	18	18.5
TC_8	23.8	24	24	24	24	24
TC_9	35.8	36	36	36	36	36
TC_10	47.8	48	48	48	48	48
TC_11	59.8	60	60	60	60	60
TC_12	71.8	72	72	72	72	72

Table 2: Soil depths for moisture measurements

Cell no.	**Cell 185**	**Cell 186**	**Cell 188**	**Cell 189**	**Cell 127**	**Cell 728**
	Depth (in)					
EC_1	5	5	5	5	6.5	8.5
EC_2	14	14	14	14	29	19.5
EC_3	17	17	17	17	36	24
EC_4	20.5	20.5	20.5	20.5		36

Temperature and moisture measurements were collected for approximately 2 years, from August 2017 to the end of 2019. Along with the ground temperature and moisture data, climate data was also collected, including air temperature, relative humidity, wind speed, net radiation and precipitation. The schematic of the plan and vertical profile views for all test cells are shown in Figure 1 (a)-(f). The location of the temperature sensors is shown using black circles; the placement of the moisture probes is shown with red symbols.

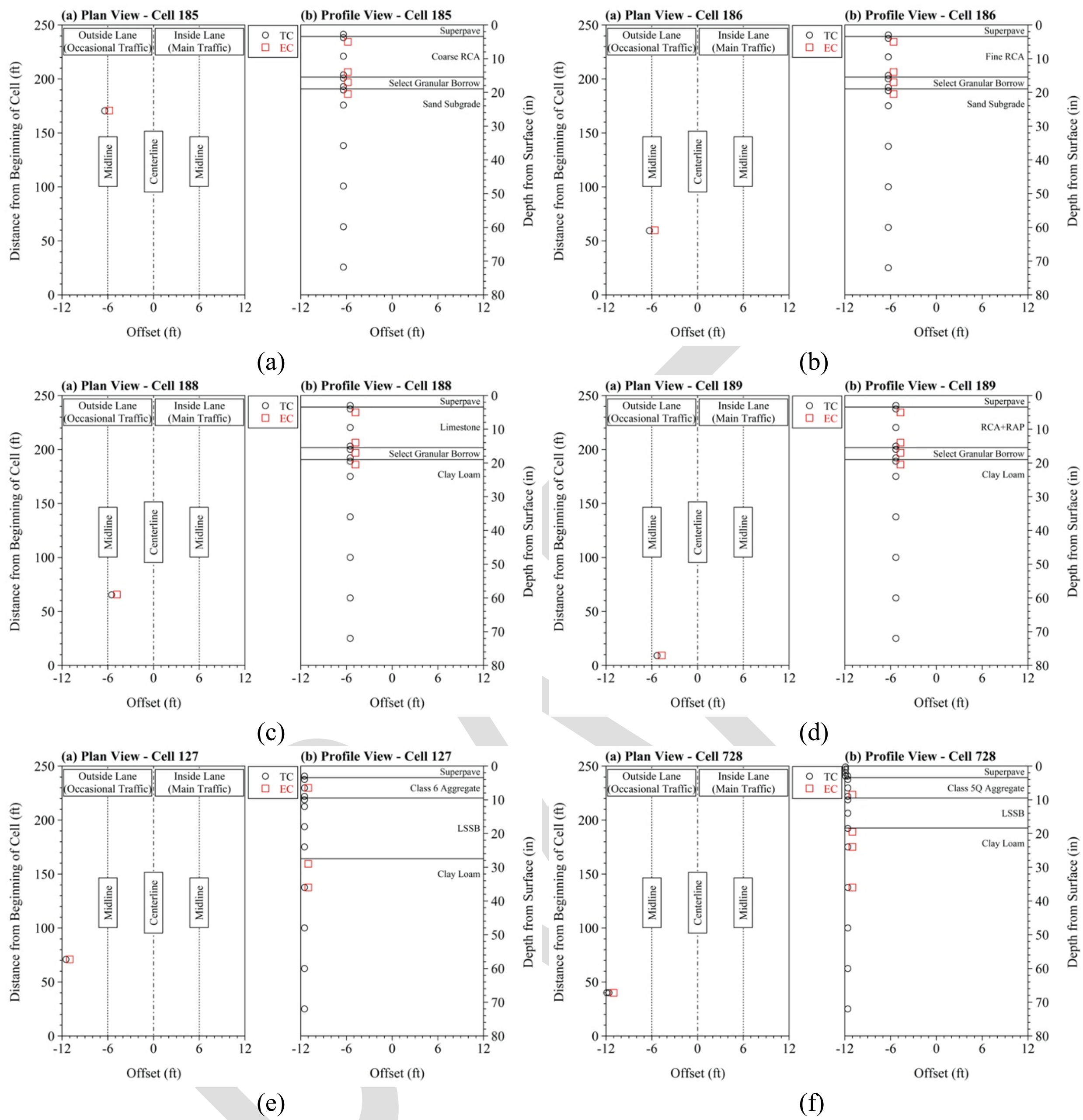


Figure 1: Schematic of the soil surfaces for temperature and moisture data collection for the locations of (a) Cell 185; (b) Cell 186; (c) Cell 188; (d) Cell 189; (e) Cell 127; (f) Cell 728

Moisture data for all test locations are also shown in Figure 2 (a-f). Apart from Cell 185, moisture data was collected across the entire data collection period at different depths.

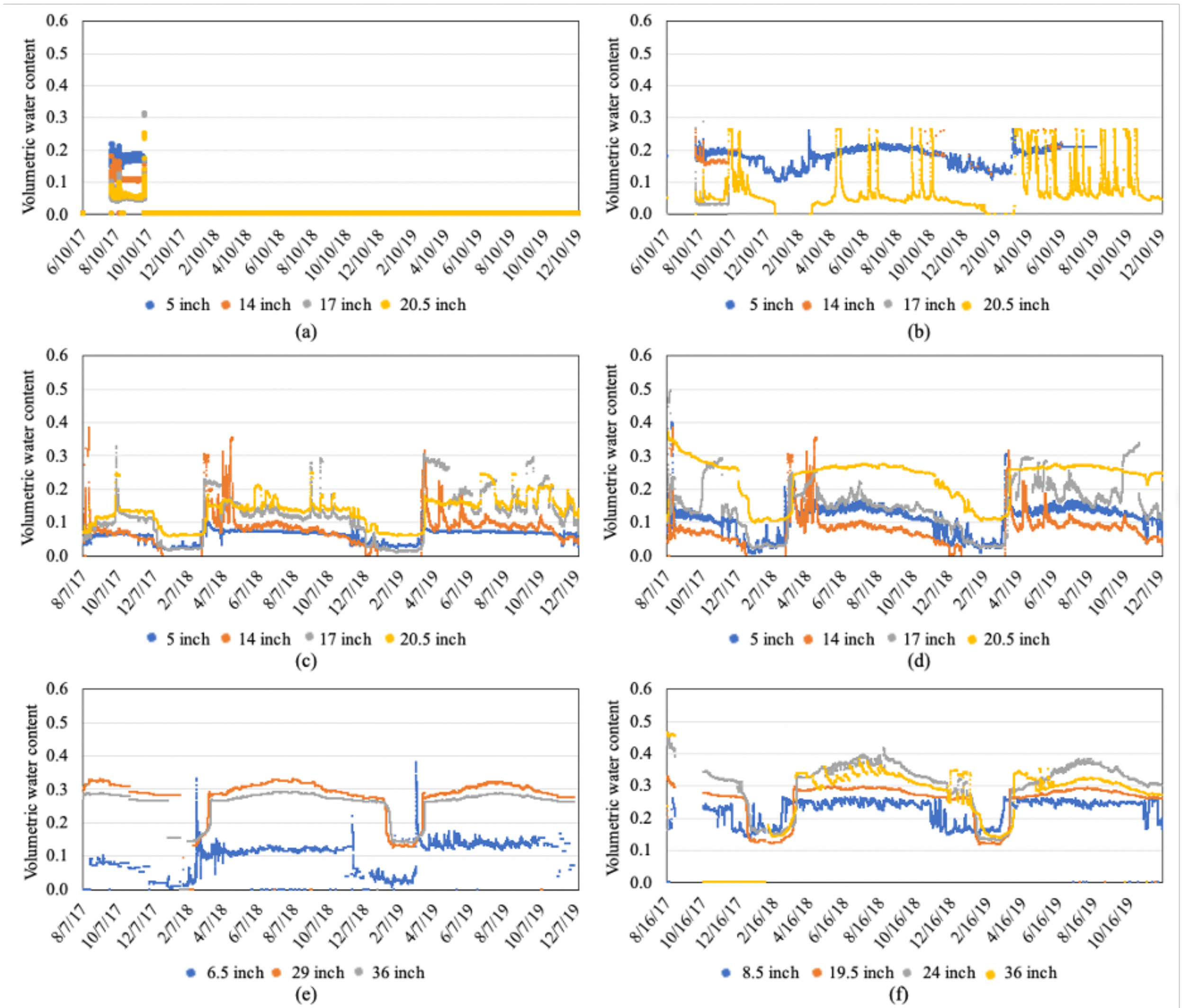


Figure 2: Moisture variation at different depths for locations (a) Cell 185, (b) Cell 186, (c) Cell 188, (d) Cell 189, (e) Cell 127, (f) Cell 728

Along with the measured data collected by the research team, previously collected ground temperatures and moisture data were collected from MnDOT. This includes long term data collected from three different counties in Minnesota, including Koochiching, Olmsted and Wright. The data in these location were available for different, but longer time spans than the above-mentioned data collected by the research team. For Koochiching, the data is comprised of two different time spans, including 2005 to 2010, and 2012 to 2019. Similarly, the data availability for Olmsted is from 2000 to 2007 and 2010 to 2017. For Wright county, data are available from 2012 to 2020. Temperature data at different depths are available for all datasets, as shown in Table 3.

Table 3: Data availability for different locations

Dataset location	Time span	Depth of temperature sensor (in)
Koochiching	2005 to 2010	1; 4; 7; 9; 12; 18; 24; 30; 36; 42; 48; 54; 60; 72; 84; 96
	2012 to 2019	1; 3; 5; 8; 12; 15; 18; 21; 24; 30; 36; 42; 48; 54; 60; 64; 78; 91
Olmsted	2000 to 2007	2.5; 6; 9; 12; 18; 24; 30; 36; 42; 48; 60; 72; 84; 96; 108
	2010 to 2017	1; 2.5; 5; 7; 13; 19; 25; 31; 37; 43; 49; 55; 61; 73; 85; 97
Wright	2012 to 2020	0.5; 2; 3.5; 5; 12; 18; 24; 30; 36; 42; 48; 54; 60; 72; 84; 96

These three datasets are available for longer timespans. However, the data was collected at 1-hour time intervals rather than 15-minute intervals. Both sets of data are used in this study since the use of both sets of data is beneficial for model development and evaluation. Next, the raw data from the above-mentioned datasets were subjected to quality control prior to use in model development. For each location, the number of missing elements was counted for all the depths separately; the percent of missing elements is shown in Table 4 and Table 5.

Table 4: Percentage of missing elements in the collected dataset in the Test Cells

	TC1	**TC2**	**TC3**	**TC4**	**TC5**	**TC6**	**TC7**	**TC8**	**TC9**	**TC10**	**TC11**	**TC12**
Cell 185	2	2	2	2	2	2	2	2	12	2	87	2
Cell 186	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	11	< 1	< 1	< 1
Cell 188	< 1	< 1	0	0	0	0	0	0	0	0	0	0
Cell 189	< 1	< 1	0	0	0	0	0	0	NA	0	0	0
Cell 127	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cell 728	< 1	< 1	< 1	0	0	0	0	0	0	0	0	0

**Note: NA: No data is available*

Table 5: Percentage of missing elements in the MNDOT collected dataset

Location	Timespan	Percentage of missing elements								
Koochiching	*2005-2010*	*TC1*	*TC2*	*TC3*	*TC4*	*TC5*	*TC6*	*TC7*	*TC8*	*TC9*
		< 1	< 1	< 1	< 1	58	< 1	< 1	< 1	< 1
		TC10	*TC11*	*TC12*	*TC13*	*TC14*	*TC15*	*TC16*	*TC17*	*TC18*
		< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	5
	2012-2019	*TC1*	*TC2*	*TC3*	*TC4*	*TC5*	*TC6*	*TC7*	*TC8*	*TC9*
		54	50	41	< 1	< 1	< 1	< 1	< 1	< 1
		TC10	*TC11*	*TC12*	*TC13*	*TC14*	*TC15*	*TC16*	*TC17*	*TC18*
		< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Olmsted	*2000-2007*	*TC1*	*TC2*	*TC3*	*TC4*	*TC5*	*TC6*	*TC7*	*TC8*	*TC9*
		7	7	7	7	7	28	7	7	7
		TC10	*TC11*	*TC12*	*TC13*	*TC14*	*TC15*			
		7	7	9	7	7	7			
	2010-2017	*TC1*	*TC2*	*TC3*	*TC4*	*TC5*	*TC6*	*TC7*	*TC8*	*TC9*
		< 1	< 1	< 1	< 1	58	< 1	< 1	< 1	< 1
		TC10	*TC11*	*TC12*	*TC13*	*TC14*	*TC15*	*TC16*		
		< 1	< 1	< 1	< 1	58	< 1	< 1		
Wright	*2012-2020*	*TC1*	*TC2*	*TC3*	*TC4*	*TC5*	*TC6*	*TC7*	*TC8*	*TC9*
		30	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
		TC10	*TC11*	*TC12*	*TC13*	*TC14*	*TC15*	*TC16*		
		< 1	46	< 1	< 1	< 1	< 1	< 1		

After removing the missing elements, outliers were identified and removed. If more than 40% data is missing, those datasets were not used for further analysis. Forward imputation [1,2], which is a sequential procedure to fill up the missing data in a step-by-step process by exploiting the data structure and interconnections among variable, was then used to fill in the missing elements.

2. CALCULATION OF FREEZE-THAW CYCLES

The occurrence of freeze-thaw cycles significantly impacts the performance of pavement systems over time. Thus, one of the objectives of this study is to evaluate the number of freeze thaw cycles occurring at different soil depths based on measured data. However, there is no widely accepted method to calculate the number of freeze-thaw cycles from soil temperature data. Freeze-thaw cycles consist of two components, including a freezing component and a thawing component (Figure 3). One freeze-thaw cycle must include both in sequential order. To ensure complete freezing, the soil temperature needs to be lower than the freezing point temperature, and after it must be higher than thaw temperature to ensure the soil is completely thawed [3].

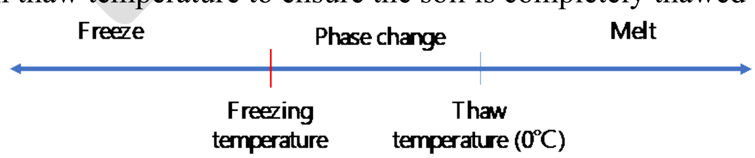


Figure 3: Freeze-thaw cycle diagram

Thus, the number of freeze-thaw cycles depend on the number of freezing and thawing temperature cycles of soils at different depths. To evaluate the number of cycles, several different methods were assessed, as follows.

2.1. Fixed freezing temperature

First, different freezing point temperatures were considered to calculate the freeze-thaw cycles while keeping the thaw temperature fixed at 0°C. 9 different freezing point temperatures were selected including -0.001°C, -0.1°C, -0.2°C, -0.25°C, -0.3°C, -0.4°C, -0.5, -0.75°C and -1°C. A value of -1°C, for example, means that when the temperature is above 0°C, it is considered to be thawed, and when the temperature is below -1°C, it is considered to be fully frozen. The variation in the number of freeze-thaw cycles for different freezing temperature widths is shown in Figure 4 for a specific test cell (Cell 185) covering 2 years of measured data.

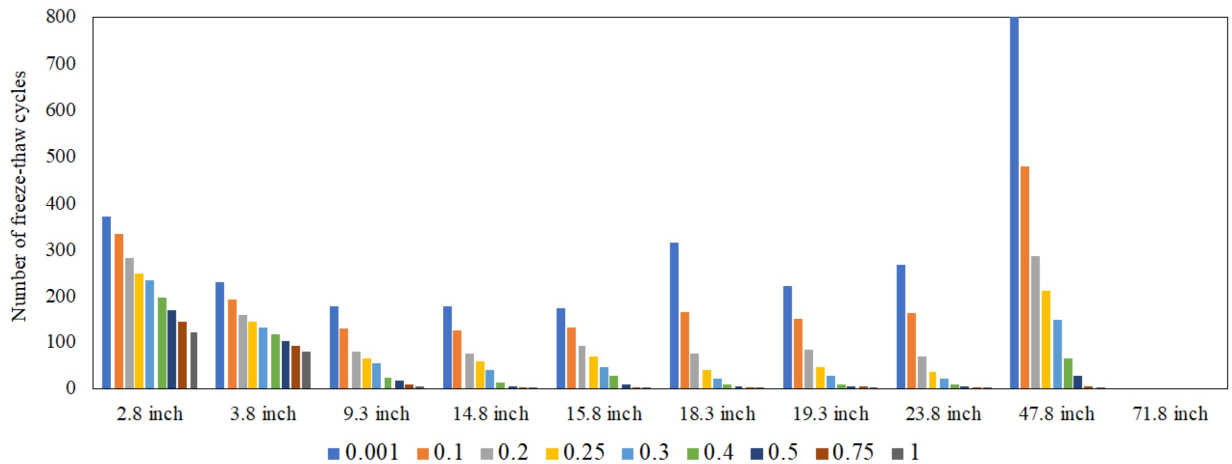


Figure 4: Variation in number of freeze-thaw cycles for different freezing point temperatures across 2 years of measured data for Cell 185

As seen in Figure 4, for freezing point temperatures closer to the thaw temperature, the number of freeze-thaw cycles for Cell 185 increases significantly. In addition, for these freezing point temperatures, the number of freeze-thaw cycles increases with increasing depth [4]. The reason that this occurs is that, at the deeper locations, the fluctuations in the temperatures are much lower than the shallower depths, thus if at the deeper locations, the temperatures fluctuation is around 0°C (e.g. at the 48 in depth in Figure 4), we see a significant increase in the count of freeze-thaw cycles when the freezing point temperatures closest to 0°C are considered. This requires careful consideration. Given that the accuracy of the temperature sensors used to collect the data is +/- 1°C, we recommend considering a -1°C freezing point temperature value to calculate the number of freeze-thaw cycles.

To assess the similarity of these counts of freeze-thaw cycles in literature, the resulting number of freeze-thaw cycles from the above-mentioned analysis was compared with a similar study where the data was collected from various locations in the state of Minnesota. In that study, the average number of freeze-thaw cycles across a 10-year period was evaluated at a depth of one inch below the surface, as shown in Figure 5. A freezing point temperature of 0°C was used in the study. As shown in Figure 5, an average of 86 cycles was found across the months of October to April.

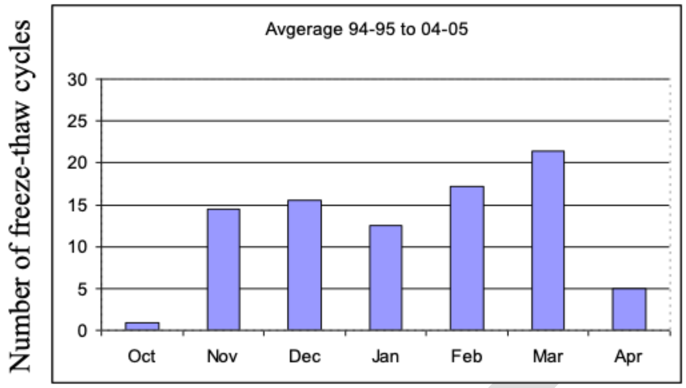
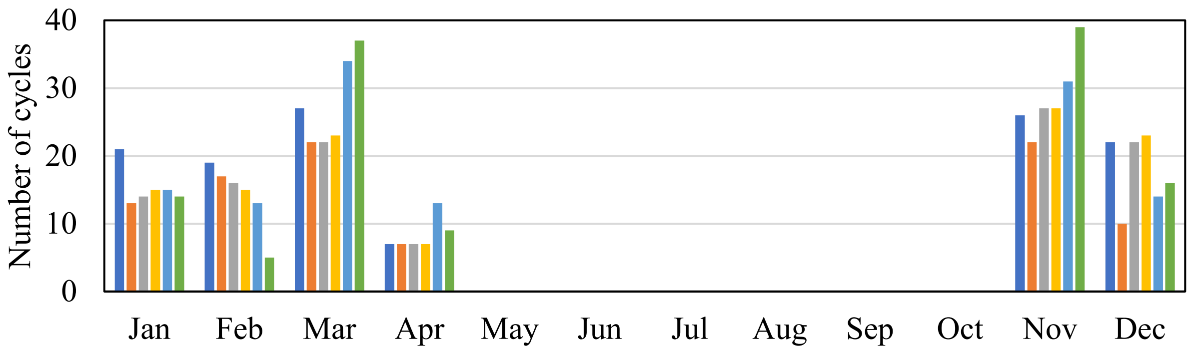
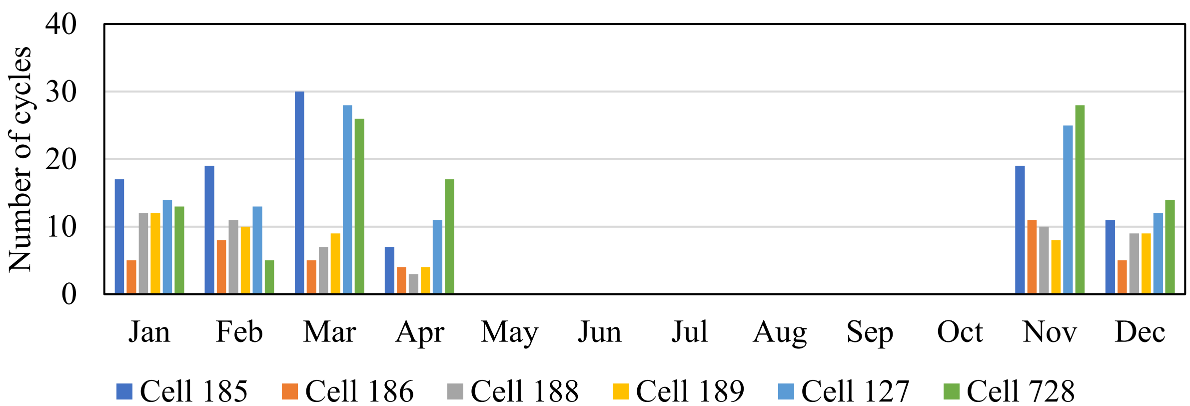


Figure 5: Average freeze-thaw cycles by month from a prior MnDOT study

In the present study, based on the measured data, a similar analysis was performed. A freezing point temperature of -1°C was used to incorporate the sensitivity of the sensors. The number of freeze-thaw cycles for the 3- and 4-inch depths in different test cells is shown in Figure 6a and 6b for the same months as the study represented in Figure 5. As shown in Figure 6, the number of cycles calculated in this study decreases with increasing depth from the surface. Similar to the previous study and Figure 5, the number of cycles is higher for the month of March at the end of winter, and during November, and at the start of the winter season.



(a)



(b)

Figure 6: Average freeze-thaw cycles by month for (a) 3-inch and (b) 4-inch depth

2.2. Modified reference temperature method

The freezing point temperature value was also calculated in a second way, to assess the impact of this method on the calculated number of freeze-thaw cycles. This method is based on *MnDOT Technical Memorandum 14-10-MAT-02*. Unlike the constant freezing point temperature method used in Section 2.1, the freezing point temperature (called the "reference temperature" in the *memorandum*) is considered to vary by the time of year. Table 6 shows this variation, as defined in the *memorandum*. The reasoning behind considering such variation is the change in solar radiation across different times of the year. This impacts the freezing and thawing behavior of the soils, particularly near the surface. Following this method while incorporating the sensitivity of the temperature sensors used to measure for data collection of +/-1°C, a "modified reference temperature" was determined (Table 6) and used to calculated the number of freeze-thaw cycles. The number of freeze-thaw cycles obtained using the "modified reference temperature" method is shown in Figure 7, using data from Cell 185.

Table 6. Reference temperature variation as defined by MnDOT Technical Memorandum 14-10-MAT-02 and modified reference temperature by time of year

Date	***Reference temperature (°C)***	***Modified reference temperature (°C)***
January 1- January 31	0	-1.0
February 1- February 7	-1.5	-1.5
February 8- February 14	-2.0	-2.0
February 15- February 21	-2.5	-2.5
February 22- February 28	-3.0	-3.0
March 1 – March 7	-3.5	-3.5
March 8 – March 14	-4.0	-4.0
March 15 – March 21	-4.5	-4.5
March 22 – March 28	-5.0	-5.0
March 29 – April 4	-5.5	-5.5
April 5 - April 11	-6.0	-6.0
April 12 - April 18	-6.5	-6.5
April 19 - April 25	-7.0	-7.0
April 26 – May 2	-7.5	-7.5
May 3- May 9	-8.0	-8.0
May 10- May 16	-8.5	-8.5
May 107 May 23	-9.0	-9.0
May 24- May 30	-9.5	-9.5
June 1- December 31	0	-1.0

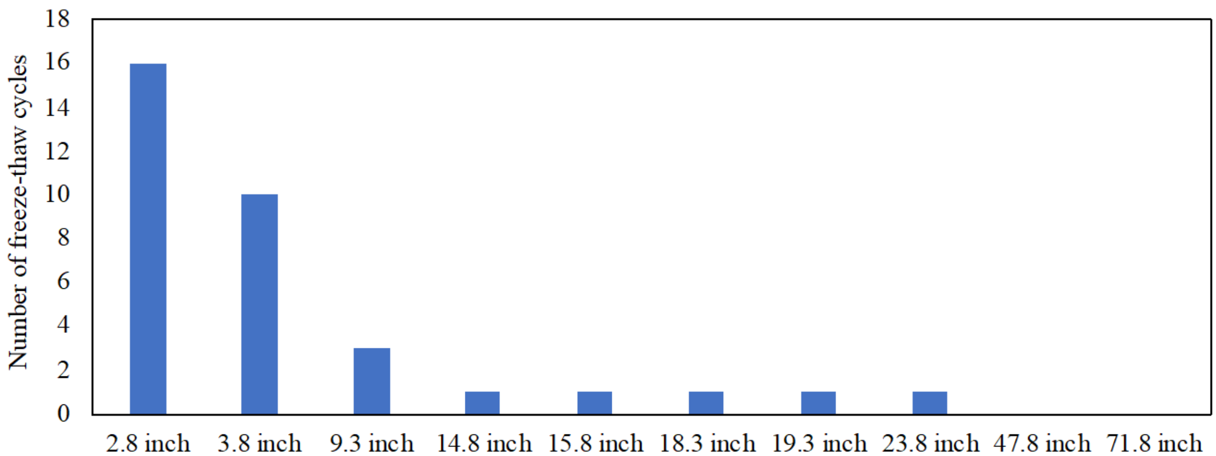


Figure 7: Number of freeze-thaw cycles obtained using *modified reference temperature* method for Cell 185

2.3. Time delay method

Another method considered in this effort includes the incorporation of a "time delay" for the purposes of ensuring that complete freezing and thawing has occurred in the studied soils. A "time delay" is defined as a minimum period of time required for a half of a freeze-thaw cycle to be completed. For example, a "time delay" of 1 hour indicates that for at least 1 hour, the studied soil must be below the freezing point temperature. An example soil temperature distribution for a single day is shown in Figure 8 which demonstrates the time delay concept for complete freezing. If the period of time below the freezing point temperature is less than 1 hour, that portion of the freeze-thaw cycle is not considered to have occurred. To complete a freeze-thaw cycle, the soil temperature needs to be higher than the thawing temperature for the time delay period to ensure complete thawing.

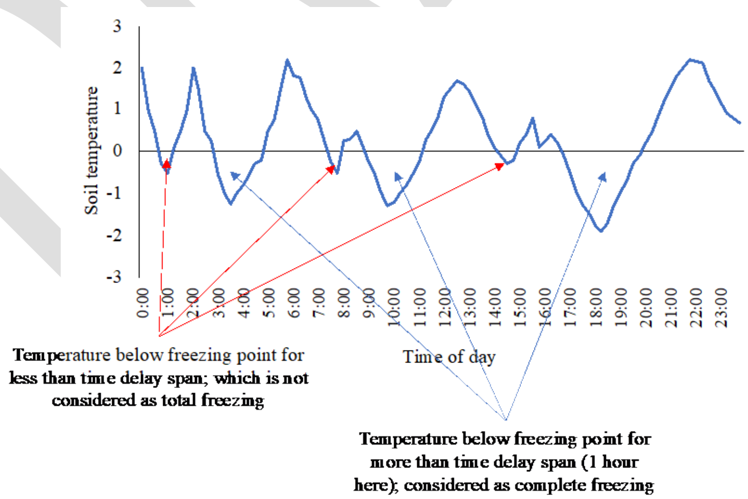


Figure 8: Schematic of the time delay scenario to calculate the number of freeze-thaw cycles

Similarly, the soil temperature must to be lower than the freezing point temperature for the designated time period to ensure complete freezing. Different time delays were considered, from 0 to 24 hours, the results of which are shown in Figure 9.

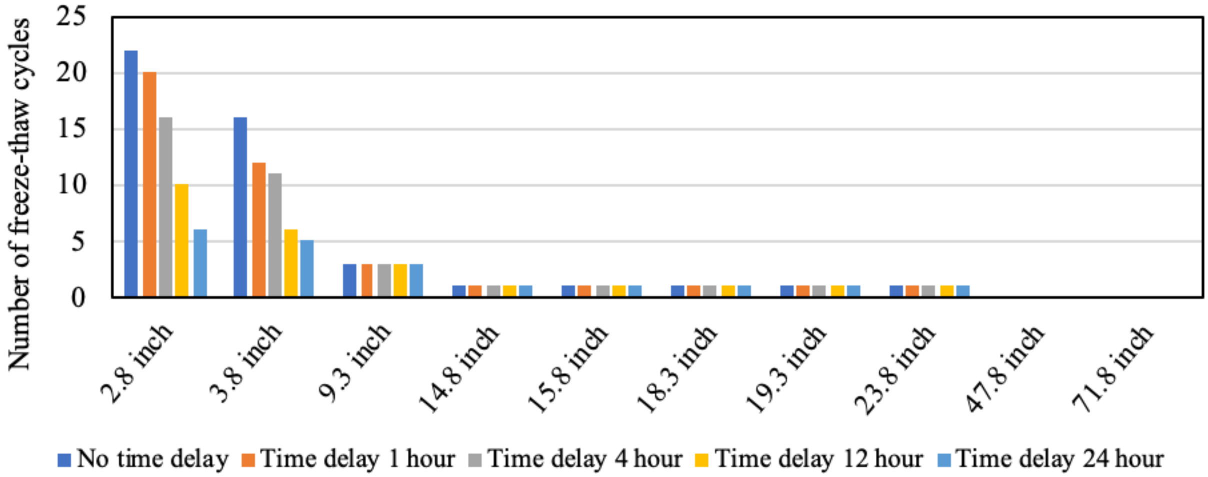


Figure 9: Number of freeze-thaw cycles using the time delay method and an assumed -1°C freezing point temperature

3. RECOMMENDATIONS

Comparing the three methods, we recommend at a minimum, the use of a fixed freezing temperature of -1°C, based on the data collected and reported sensor error of +/- 1°C. When using this fixed freezing temperature of -1°C, the additional use of the time delay method impacts only the shallow depths of temperature measurements. Further studies are needed to finalize the appropriate method to calculate the number of cycles.

4. REFERENCES

[1] Barnard, John, and Xiao-Li Meng. "Applications of multiple imputation in medical studies: from AIDS to NHANES." Statistical methods in medical research 8, no. 1 (1999): 17-36.

[2] Solaro, Nadia, Alessandro Barbiero, Giancarlo Manzi, and Pier Alda Ferrari. "A sequential distance-based approach for imputing missing data: Forward Imputation." Advances in Data Analysis and Classification 11, no. 2 (2017): 395-414.

[3] Technical Memorandum No. 14-10-MAT-02, MINNESOTA DEPARTMENT OF TRANSPORTATION, October 7, 2014

[4] Zegeye Teshale, Eyoab, Dai Shongtao, and Lubinda F. Walubita. "Evaluation of Unbound Aggregate Base Layers using Moisture Monitoring Data." Transportation Research Record 2673, no. 3 (2019): 399-409.