Long Term Pavement Performance Computed Parameter: Frost Penetration

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LTPP

FOREWORD

In-situ data availability is vital to pavement engineering. As the pavement design process moves toward mechanistic-empirical techniques, knowledge of seasonal changes in pavement structural characteristics becomes critical. Specifically, frost penetration information is necessary for determining the effect of freeze and thaw on pavement structural responses. This report describes a methodology for determining frost penetration in unbound pavement layers and subgrade soil using electrical resistivity, moisture, and temperature data collected for instrumented Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) sites. The report also contains a summary of LTPP frost depth estimates and a detailed description of the computed parameter tables containing frost penetration information for LTPP SMP sites.

The report will be of interest to highway agency engineers as well as researchers who will use the LTPP frost penetration data to improve pavement design and analysis procedures. In addition to the information from the LTPP in service pavements, a method for monitoring frost depth presented in this report can be utilized by State highway agencies interested in monitoring freeze-thaw conditions in unbound pavement layers.

Gary L. Henderson
Director, Office of Infrastructure
Research and Development

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As the pavement design process moves toward mechanistic-empirical techniques, knowledge of seasonal changes in pavement structural characteristics becomes critical. Specifically, frost penetration information is necessary for determining the effect of freeze and thaw on pavement structural responses. This report describes a methodology for determining frost penetration in unbound pavement layers and subgrade soil using temperature, electrical resistivity, and moisture data collected for instrumented Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) sites. The report also contains a summary of LTPP frost depth estimates and a detailed description of the LTPP computed parameter tables containing frost penetration information for 41 LTPP SMP sites. The frost penetration analysis methodology and the accompanying E-FROST program is used in-situ soil temperature as a primary source of data to predict frost depth in unbound pavement layers. In addition to temperature data, electrical resistivity and moisture data were used as supplemental data sources for the analysis when temperatures were close to the freezing isotherm. The Enhanced Integrated Climatic Model (EICM) was used to fill intermediate gaps in the measured soil temperature data.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1. INTRODUCTION

BACKGROUND

Importance of Frost Penetration Information

Knowledge of frost penetration beneath the pavement structure is critical for many pavement design, analysis, and management applications. Problems caused by frost include the seasonal change in the bearing capacity of soils brought by freezing and thawing. As subsurface temperatures decrease, the moisture in the unbound pavement layers freezes into ice that binds the aggregate particles together. Frost penetration leads to an increase in the strength and stiffness of the unbound pavement layers and subgrade soil. The process of ice formation also draws moisture into the freezing zone. When the frost thaws in the spring, the moisture increase in the soil can lead to weakened support for the pavement structure.

Another mechanical process associated with frost is the volumetric change in frost-susceptible soils, referred to as frost heave, which can lead to vertical differential movements of the road and subsequent poor performance. This heaving of roadbeds out of vertical alignment and breaking of the pavement surface often complicates highway maintenance.

Over the years, the National Oceanic and Atmospheric Administration (NOAA)(1) and Environment Canada(2) have developed and published the climatic maps containing historical frost penetration values, as well as the number of freeze-thaw cycles in the form of contour maps. These maps provide frost depth estimates for natural (uncovered) land in the United States and Canada. The frost penetration conditions under pavements may be different from that of exposed land surfaces. In addition, deicing salts may have an effect on frost penetration as they eventually dissipate into the soil.

Seasonal Monitoring Program

To provide the transportation community with the data needed to understand the magnitude and impact of diurnal, seasonal, and annual variations in pavement properties and responses, including the effects of frost penetration beneath pavement section, the Federal Highway Administration (FHWA) Long Term Pavement Performance (LTPP) program selected a number of test sites throughout the United States and Canada for the Seasonal Monitoring Program (SMP).

The original SMP (hereto referred as SMP I) included a total of 65 test sections and lasted from 1992 to 1999. As a part of the SMP I experiment, 37 pavement test sections were instrumented with electrical resistivity (ER) probes to monitor the frost penetration in unbound pavement layers. In addition, these sections were instrumented with time domain reflectometry (TDR) and temperature probes.

At the conclusion of SMP I, the LTPP team realized the need for additional monitoring of these sites and initiated the SMP II program. The objective of the SMP II monitoring was to continue providing the data needed to attain a fundamental understanding of the magnitude and impact of variations in pavement response and properties due to the separate and combined effects of temperature, moisture, and frost penetration. The SMP II included a total of 22 test sections and lasted from 2000 to October 2004. LTPP continued monitoring the ER trend as a part of the SMP II experiment at 12 test sites.

To aid in the interpretation of the ER data, an interactive computer program called FROST was developed in the late 1990s, and the available data were analyzed (see FHWA-RD-99-088 for more information on FROST).[3] FROST used ER data (voltage, contact resistance, and resistivity) in conjunction with soil temperature data to determine the depth of frost penetration in unbound layers for the SMP sections.

The results of frost penetration analysis are stored in two computed parameter tables in the LTPP database as follows:

- SMP_FREEZE_STATE.
- SMP_FROST_PENETRATION.

The SMP_FREEZE_STATE table characterizes the freeze state as frozen or nonfrozen at each ER measurement depth. This information is useful for understanding or re-evaluating the process by which the results presented in table SMP_FROST_PENETRATION were derived. The data in table SMP_FROST_PENETRATION translate the freeze state at each measurement depth into starting and ending depths of frozen layer(s). The SMP_FROST_PENETRATION table is the end product of the data analysis to determine the boundaries of frozen layers within the pavement cross-section. These computed parameters tables contain information necessary analyzing the changes in pavement structural responses due to the seasonal changes in pavement layer properties.

These tables were updated twice with the new batches of the processed data: the first upload was based on the July 1999 version of the LTPP data for SMP I sections, and the second upload included SMP II sections based on the July 2001 version of the LTPP data. With the completion of monitoring measurements on the SMP sections in October 2004, there was a need to complete the interpretation of measurements not previously interpreted and to add the results to the database. In addition, through previous interpretation of SMP ER and soil temperature data, it became evident that the accuracy of the LTPP frost predictions could be improved by adding thermodynamic analysis capability to estimate missing temperature readings and by cross-referencing ER trends with moisture and temperature changes.

PROJECT OBJECTIVE AND SCOPE

The objective of the current project was to update and complete the interpretations of frost penetration using measurements collected at the instrumented SMP sites. To achieve this objective, the project team was charged to review and enhance LTPP procedures for frost penetration determination. The enhanced procedures were subsequently used to critically review and flag questionable previous frost estimates and to complete the interpretation of frost depth in the unbound layers for new data and to update previous estimates.

The project was divided into two phases. The objectives of Phase I were to assess the existing LTPP frost penetration analysis methodology and frost penetration results, propose enhancements to the LTPP frost penetration analysis process, and develop a detailed research plan that would include the proposed enhancements for the frost penetration determination procedures. The objectives of Phase II were to implement these procedures in a software research tool, conduct frost penetration analysis, and develop new LTPP frost predictions using SMP data.

REPORT OVERVIEW

This final report documents the investigations performed during the study, describes the enhancements to the frost penetration analysis methodology developed, and summarizes the results of frost penetration estimates for LTPP SMP sections. Activities performed throughout the remainder of this report are discussed as follows:

- Chapter 2. Review of LTPP Frost Procedures and Assessment of Previous Estimates.
- Chapter 3. Review of Advances in the State of Knowledge in Frost Penetration Analysis.
- Chapter 4. Enhanced Methodology for LTPP Frost Determination.
- Chapter 5. Implementation of the Enhanced Frost Analysis Methodology.
- Chapter 6. LTPP Data Used for Frost Determination.
- Chapter 7. Frost Penetration Analysis Results.
- Chapter 8. Summary and Recommendations.

In addition, the following two appendices are provided with the report:

- Appendix A. E-FROST User's Guide.
- Appendix B. List of Inputs to the EICM Program.

CHAPTER 2. REVIEW OF LTPP FROST PROCEDURES AND ASSESSMENT OF PREVIOUS ESTIMATES

LTPP SMP DIRECTIVES AND EXPERIMENT DESIGN

To obtain a better understanding of the early LTPP frost depth determination procedures, the LTPP reports, SMP directives, software, and other literature relating to detection of frost in unbound pavement layers were obtained and reviewed in detail. In addition, a coordination meeting took place between the Data Analysis Technical Support (DATS) team, FHWA/LTPP team and regional service centers, and Technical Support Services Contract (TSSC) representatives. The review included SMP installation/de-installation reports, the procedures and equipment used to collect data needed for the interpretation of LTPP ER and TDR data, and the quality control (QC) procedures used to evaluate the SMP data prior to upload into the database, all of which include the following documents: (See references 3, 4, 5, 6, 7, 8, 9.)

- *Determination of Frost Penetration in LTPP Sections,* Report No. FHWA-RD-99-088.
- *FHWA, LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines*, Report No. FHWA-RD-94-110.
- FHWA, LTPP Guidelines for SMP Phase II Equipment and Instrumentation Installation, SM-35.
- *FHWA, LTPP SMP Phase II Monitoring*, SM-31.
- LTPP Seasonal Monitoring Program SMP II Equipment Installation/De-Installation Reports prepared by LTPP Regional Contractor Offices for individual sites.
- *Computed Parameters: Freeze/Thaw Monograph for LTPP*. Publication No. FHWA-RD-98–177.
- *FHWA, LTPP Information Management System, IMS Quality Control Checks.*

In the SMP I experiment, 37 test sites were instrumented to measure ER, the moisture content, and temperature in the unbound pavement layers (base and subbase) and the upper layers of subgrade. The LTPP SMP instrumentation layout is shown in figure 1. The techniques, equipment, and schemes of data collection under the SMP are described in detail in the *LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines,* Report No. FHWA-RD-94-110.[4] This section of the report provides a summary of how temperature, moisture, and ER data are collected and their relevance to frost penetration in pavement layers.

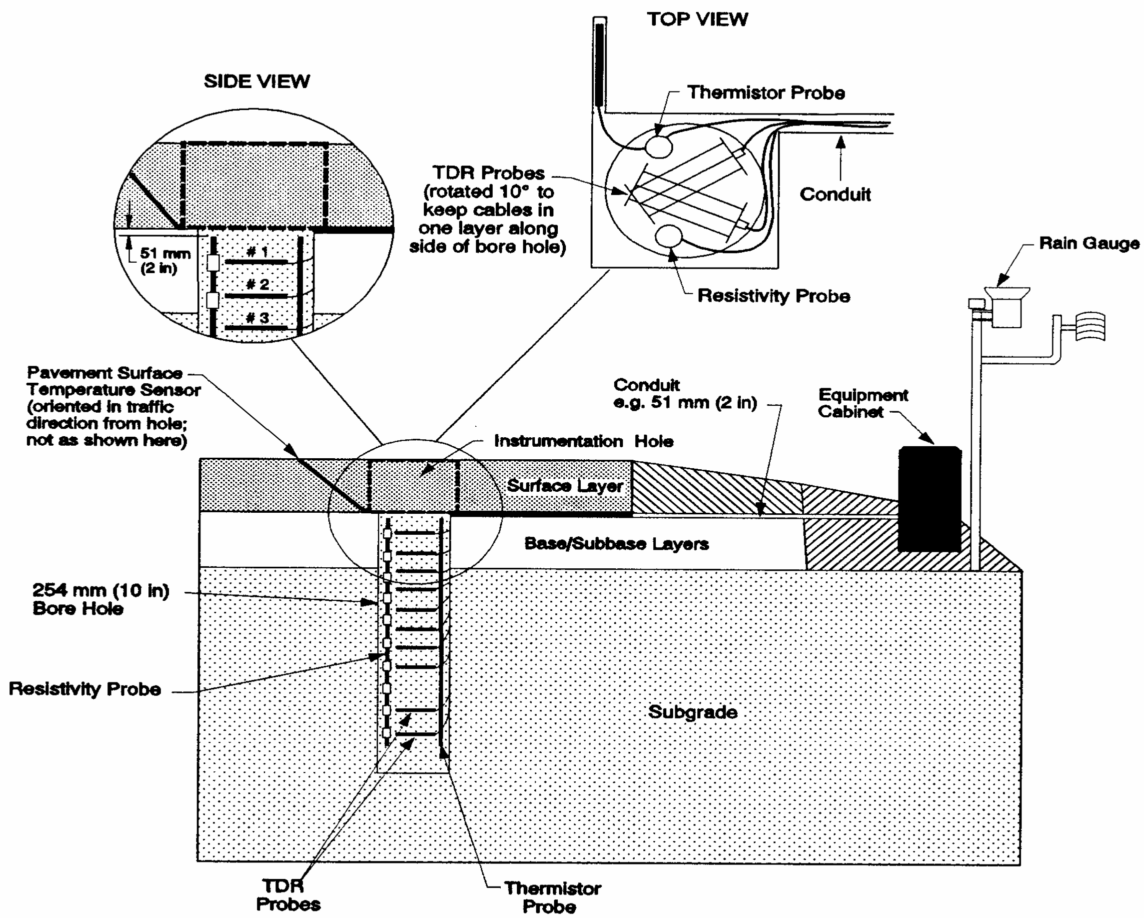


Figure 1. Illustration. LTPP SMP instrumentation layout.[4]

Electrical Resistivity Measurements

The electrical resistivity probes used in the initial SMP program were developed by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL). The probes were installed to monitor the freeze state in the unbound pavement layers and the top subgrade layers. Each resistivity probe consists of 36 metal wire electrodes spaced 51 mm (2 inches) apart on a solid polyvinyl chloride (PVC) rod 1.9 m (73 inches) long. The top of the resistivity probe was installed approximately 50 mm (2 inches) below the bottom of the lowest bound pavement layer. The weakness with this multiplexer was that there was no reference to check the voltage outputs recorded.

In the SMP II experiment, the CRREL multiplexer was replaced with an ERB20 multiplexer, manufactured by ABF Manufacturing, Inc. This multiplexer provides an input voltage at the start of each cycle and reference voltage through a 100k resistor at the completion of the cycle.

The electrical resistivity technique is based on the fact that the bulk resistivity of a soil increases dramatically when the soil freezes. Electricity is conducted exclusively by the pore water contained in the soils because the soil minerals and air voids are nonconductive. The electrical resistivity of frozen water is much higher than that of liquid water, and this difference is used to differentiate between frozen and unfrozen soil. However, if water content is low, or if the water phase is discontinuous, the difference in electrical resistivity between the frozen and unfrozen soil is difficult to detect reliably.

For SMP I, the automated and manual resistivity profiles were collected at the time of the Falling Weight Deflectometer (FWD) data collection to evaluate changes in layer stiffness based on the soil properties. As a result, only limited ER measurements were taken at the time of FWD data collection for the majority of LTPP sites: once a month or less every other year for SMP I sites and six months a year for SMP II noncontinuous sites. During the SMP II experiment, more extensive ER data were collected at selected continuous monitoring sites.

The challenge working with ER data is that the majority of data were not collected continuously, except at a few SMP II sites that were set up for continuous monitoring. Sparse measurements make it difficult to capture the beginning and ending of freezing and thawing periods. Changes in ER equipment and measuring techniques also created challenges when comparing the values collected during the SMP I and SMP II experiments.

For the SMP I experiment, ER data were stored in the following tables:

- SMP_ERESIST_AUTO.
- SMP_ERESIST_MAN_CONTACT.
- SMP_ERESIST_MAN_4POINT.

Since the launch of the SMP II program, the collection, processing, and storage of ER data for SMP II sites has been modified. The SMP II ER data are collected using different continuous automatic equipment and are stored in the following tables:

- SMP_ERESIST_ABF_REF_VA— Applied voltage and resistance voltage values measured on the internal reference resistor used in ABF multiplexer.
- SMP_ERESIST_AUTO_ABF—Resistance voltage and computed resistance for ABF type resistivity probe.

The sites that were moved from the SMP I experiment to the SMP II experiment have ER data collected prior to 2000 in the old ER data tables and ER data collected after 1999 in the new data tables. In addition, manually collected ER data are stored in the tables used in SMP I.

Moisture Measurements

The volumetric moisture content (VMC) is determined using TDR probes placed at approximately 10 depths in the unbound base, subbase (if present), and subgrade layers. The VMC represents a ratio of the volume of water to the total volume (soil solids + water + voids). The probe closest to the pavement surface was installed at the mid-height of the highest unbound layer unless that layer was more than 300 mm (12 inches) thick, in which case the probe was installed 150 mm (6 inches) below the top of the layer regardless of thickness. The next seven probes were installed at 150-mm (6-inch) depth intervals, and the two deepest probes were installed at 300-mm (12-inch) depth intervals, thereby placing the deepest probe approximately 1.8 m (6 ft) below the top of the highest unbound pavement layer.

The data collected with the TDR instrumentation are used to determine the dielectric constants for the soil. The volumetric moisture content is then computed using regression equations relating the dielectric constant to moisture content, which are discussed in Report No. FHWA-RD-99-115.[10] The results from the recently completed LTPP data analysis study *LTPP Computed Parameter: Moisture Content,* Report No. FHWA-HRT-08-030,[22] contain computed volumetric moisture content values estimated based on the dielectric constant and properties of soil using calibrated micromechanics equation. These results are included in the LTPP table MP_TDR_MOISTURE.

Since the dielectric constant for ice is significantly different than that for water, the water contents measured by the TDR probes during the frozen periods may reflect the presence of ice.

Like the ER data, the majority of TDR data were not collected continuously, except at a few SMP II sites that were set up for continuous monitoring. Sparse measurements make it difficult to capture the beginning and ending of freezing and thawing periods.

Temperature Measurements

The temperature profile is measured by thermistors installed at 18 depths through pavement structure. The thermistors are permanently installed in a 0.25-m (10-inch) diameter hole located near the section end. The first three thermistors are embedded in the surface bound layer, and the rest are embedded in the base, subbase, and subgrade layers. The five thermistors closest to the pavement surface are spaced 75 mm (3 inches) apart. The rest are spaced 150 mm (6 inches) apart. Data from the first five thermistors are recorded hourly. Daily temperature statistics, including maximum, minimum, average temperature, and times of maximum and minimum temperature, are recorded for all thermistors in table SMP_MRCTEMP_AUTO_DAY_STATS.

Subsurface temperature measurements are taken every day, providing a complete picture of temperature changes in subsurface layers throughout the year. Seasonal temperature trends can be used to correlate temperature, moisture, and ER data. From these correlations, it is possible to establish freezing and thawing temperatures, freezing isotherm, and the freeze state of the soil for a given SMP section.

INITIAL LTPP FROST INTERPRETATION METHODOLOGY

Previous LTPP frost penetration methodology is documented in *FHWA, Determination of Frost Penetration in LTPP Sections,* Report No. FHWA-RD-99-088.[3] This report was reviewed in detail to obtain a thorough understanding of the procedures used to generate the existing LTPP computed parameter tables with regard to frost depth in unbound pavement layers. The previous method used to determine SMP_FREEZE_STATE and SMP_FROST_PENETRATION is shown in the flowchart in figure 2.

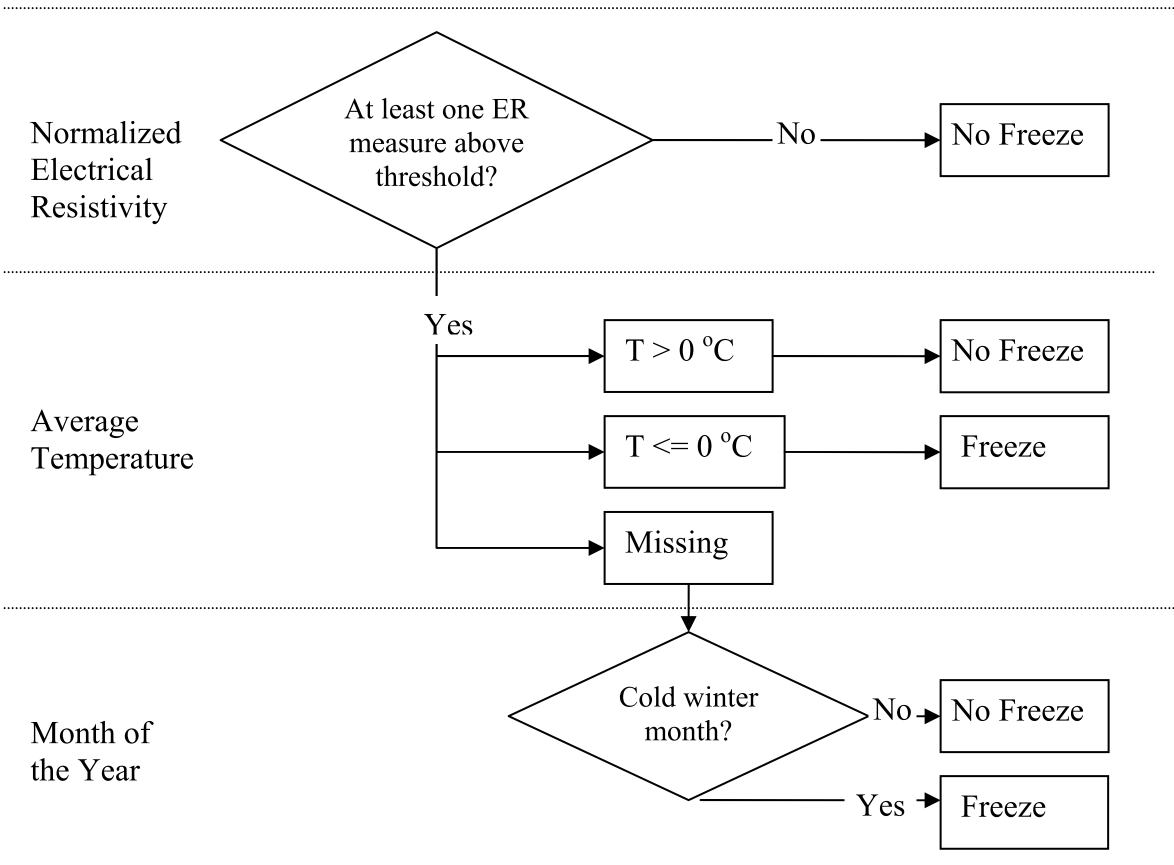


Figure 2. Chart. Previous FROST decision tree.

Upon review of the SMP I and II experimental designs and LTPP frost analysis methodology, the following shortcomings and potential future improvements were identified:

- Evaluations of frost penetration were made only for the dates when ER measurements were taken. With the exception of a few SMP II sites, these early measurements were taken once a month or less frequently. Thus, ER data were insufficient to establish the frost penetration profile for the whole freeze season.
- ER time-series trends were difficult to interpret due to frequent unexplained fluctuations in ER values and sometimes counterintuitive trends (i.e., low ER in winter and high ER in summer). At the same time, temperature trends appeared to be very reliable and correlated well with changes in air temperature and with the Enhanced Integrated Climatic Model (EICM)-based subsurface temperature changes with time.
- Subsurface temperatures were considered in the frost analysis only when ER data were available. However, these temperatures were available for nearly every day of the year. More extensive use of the temperature data could have improved the accuracy of frost estimates.
- Moisture content data were not included in the FROST interactive procedure. Use of moisture data could improve the determination of the freeze state, especially at the beginning of the freezing and thawing periods.

PREVIOUS LTPP FROST ESTIMATES

Previously estimated frost information stored in the SMP_FREEZE_STATE and SMP_FROST_PENETRATION tables was reviewed during the study. The estimates were available for 37 SMP I sections and 12 SMP II sections and are listed in table 1 for the period from 1994 to 2001.

Table 1. LTPP section with previous frost depths estimates.

STATE_CODE	SHRP_ID	SMP I	SMP II	State
4	1024	Y		Arizona
8	1053	Y		Colorado
9	1803	Y		Connecticut
16	1010	Y		Idaho
18	3002	Y		Indiana
20	4054	Y		Kansas
23	1026	Y		Maine
24	1634	Y		Maryland
25	1002	Y		Massachusetts
27	1018	Y		Minnesota
27	1028	Y		Minnesota
27	4040	Y		Minnesota
27	6251	Y	Y	Minnesota
30	0114	Y	Y	Montana
30	8129	Y		Montana
31	0114	Y	Y	Nebraska
31	3018	Y	Y	Nebraska
32	0101	Y	Y	Nevada
32	0204	Y		Nevada
33	1001	Y		New Hampshire
36	0801	Y	Y	New York
36	4018	Y		New York
39	0204	Y		Ohio
39	0901	Y	Y	Ohio
42	1606	Y	Y	Pennsylvania
46	0804	Y	Y	South Dakota
46	9187	Y		South Dakota
48	1077	Y		Texas
49	1001	Y		Utah
49	3011	Y		Utah
50	1002	Y	Y	Vermont
56	1007	Y		Wyoming
83	1801	Y	Y	Manitoba
83	3802	Y		Manitoba
87	1622	Y		Ontario
89	3015	Y	Y	Quebec
90	6405	Y		Saskatchewan

The primary method of reviewing the LTPP frost estimates was by examining the ER, moisture, and temperature data collected as part of the SMP study and then comparing the trends observed in these data with freeze estimates obtained from the LTPP database. During the review, the following potential data problems and drawbacks of previous methodology were identified:

- Limited ER data availability.
- Unexplained fluctuations in ER values.
- Questionable noncontinuous frost regions.
- Noninclusion of moisture data.
- Underutilization of temperature and moisture data.

The results of review are discussed in detail in the following subsections.

Limited ER Data Availability

The sparse ER data put limitations on the accuracy and validity of the frost estimates. The example in figure 3 demonstrates the limitation of the frost penetration estimates attributed to limited ER data availability. The example shows a comparison between frost predictions based on ER and temperature data for SMP II section 0114 in Montana for the 2000–2001 winter season. The frost penetration profile based on ER probe measurements is laid over the freeze state predictions based on subsurface temperature profile, as shown in the graph's legend. Blue "Freeze" cells indicate temperatures below -1 ^{o}C. Grey "No Freeze" cells indicate temperatures above 0 ^{o}C. Yellow cells indicate temperatures between 0 ^{o} and -1 ^{o}C. Burgundy cells indicate a freeze state based on ER data.

As can be seen from the plot, ER data were collected almost daily during November 2000. Frost predictions show agreement between temperature-based and ER-based predictions for this period. However, no ER data were collected again until January 8, 2001. As a result, the LTPP database contains no frost penetration predictions for December 2000, while temperature data strongly suggest a freeze state up to 1 m (3.28 ft) in depth, as indicated by the blue region. After data collection on January 8, 2001, no ER measurements are reported until mid March 2001, completely missing the spring thaw period.

Figure 4 shows a comparison of ER, temperature, and moisture trends for the same site, as evaluated 0.52 m (1.71 ft) below the pavement surface. ER and moisture data are reported on the left axis. ER data are normalized between 0 and 1 to provide better means for analysis of seasonal fluctuations. Temperature data are reported in degrees (^{o}) Celsius on the right axis. The following can be observed from this figure:

- All three types of measurements show an "as-expected" trend—as temperature falls below 0 ^{o}C, ER values increase and moisture values decrease.
- Spring thaw is clearly defined by a sharp increase in moisture values.
- Temperature and moisture data are more complete compared to ER data, providing a better indication of freezing conditions in this case.

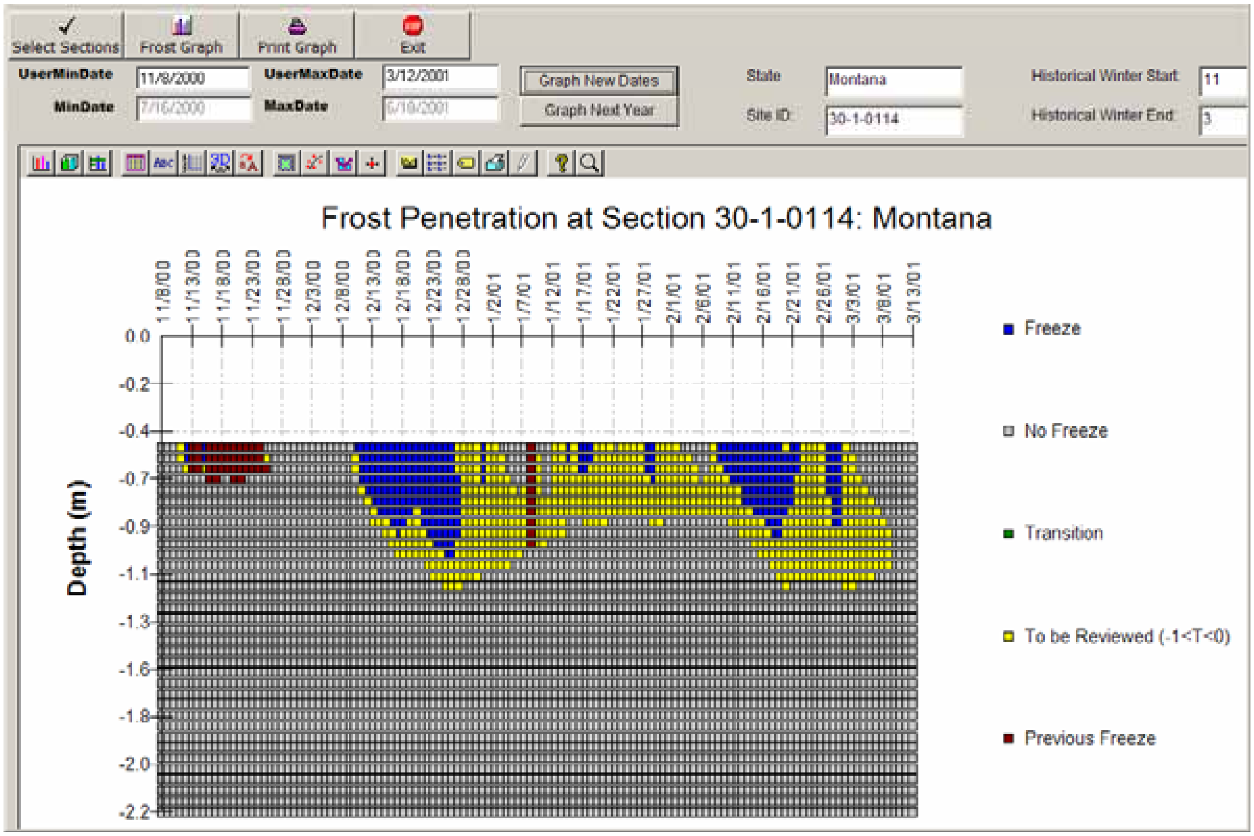


Figure 3. Chart. Frost predictions for section 0114 in Montana.

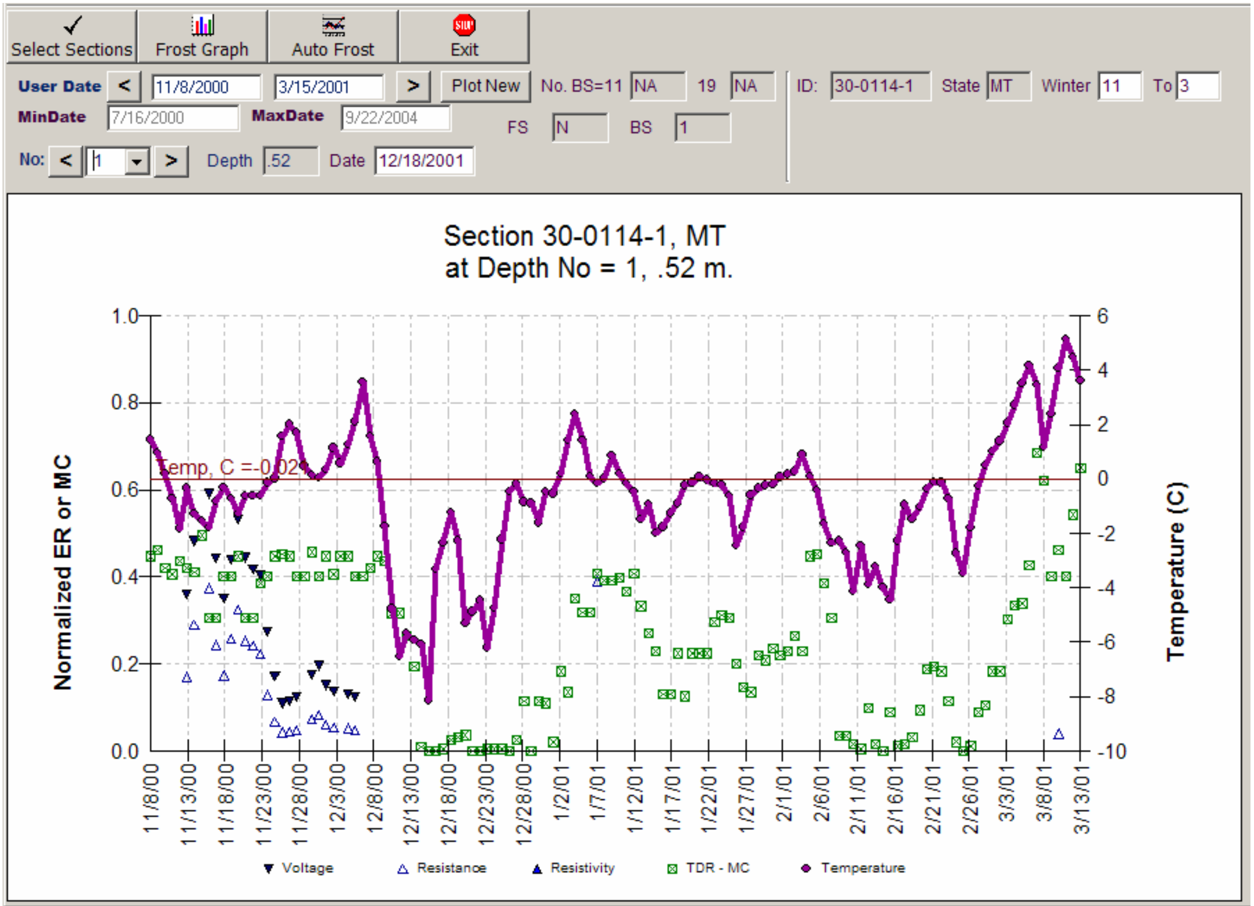


Figure 4. Chart. Comparison of ER, temperature, and moisture trends for section 0114 in Montana.

Figure 5 shows frost predictions for SMP I site 1028 in Minnesota. While most ER-based frost predictions (marked as “Previous Freeze” on the plot) follow the temperature-based frost predictions, it is evident that ER-based frost estimates are more questionable when temperatures are between 0 ^{o}C and -1 ^{o}C (see yellow section of the plot). The state of soil may be in transition between frozen and unfrozen for these temperatures.

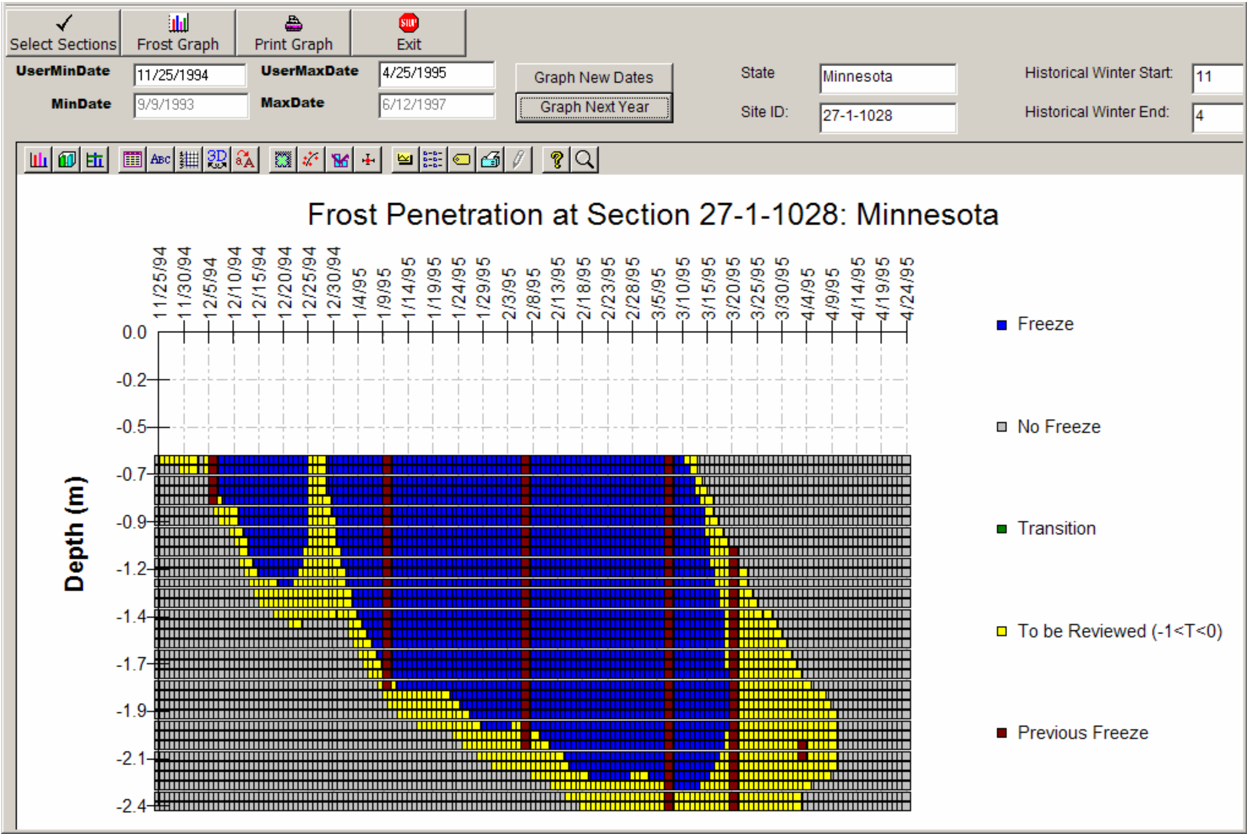


Figure 5. Chart. Frost predictions for section 1028 in Minnesota.

Fluctuations in ER Values

Review of the ER data pointed to the instability in ER trends—ER values may go down during freezing temperatures and up during hot summer months, although the opposite trend is expected. Because the previous methodology relies heavily on the ER data, such ER trends may result in inaccurate frost estimates.

Figure 6 illustrates the failure to predict frost penetration at lower depths where soil temperature remained below -1 ^{o}C for extended periods of time. The reasons for inaccurate frost predictions include subjectivity when establishing an ER threshold value and unexplained dips in ER values during the cold season. Figure 7 shows changes in ER, moisture, and temperature values with time at a depth of 1.01 m (3.31 ft). Examination of the temperature data in figure 7 indicates that freezing at that depth occurred during mid to late December. The freezing process was accompanied by a constant temperature around 0 ^{o}C for several days while heat loss took place. After that period, the soil temperature fell below 0 ^{o}C, indicating a freeze state. The soil remained frozen until mid March, when temperatures rose above 0 ^{o}C and moisture content increased. Moisture content values decreased sharply between December and April, also indicating a “Freeze” condition.

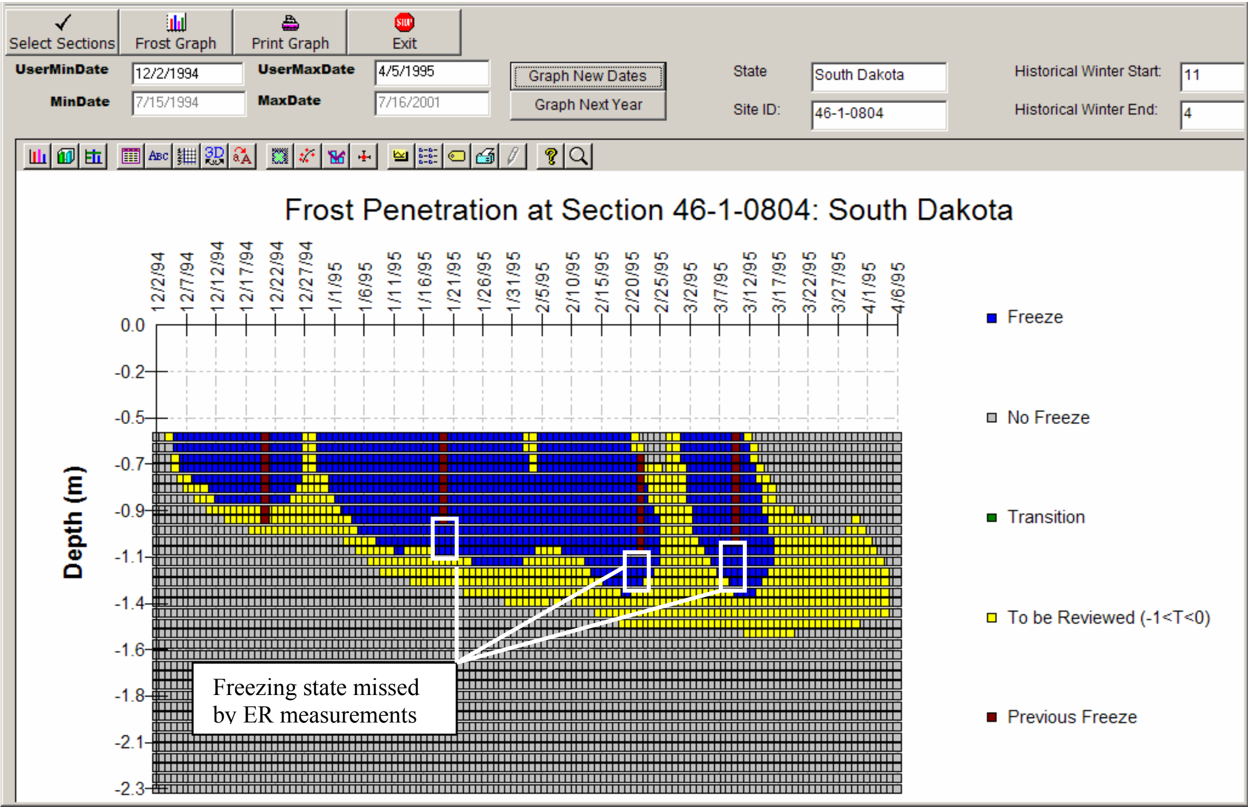


Figure 6. Chart. Frost predictions for section 0804 in South Dakota for 1994–1995 winter season.

The example in figure 7 shows high fluctuations in resistivity values taken in February and then in early March 2005. The ER values differ by over 80 percent, although temperature and moisture data indicate that the soil remained frozen for both dates.

Further data review indicates that the accuracy of ER predictions had improved once the same sections became part of the SMP II continuous monitoring experiment. However, ER-based determination of frost penetration for temperatures just below the freezing point remained challenging.

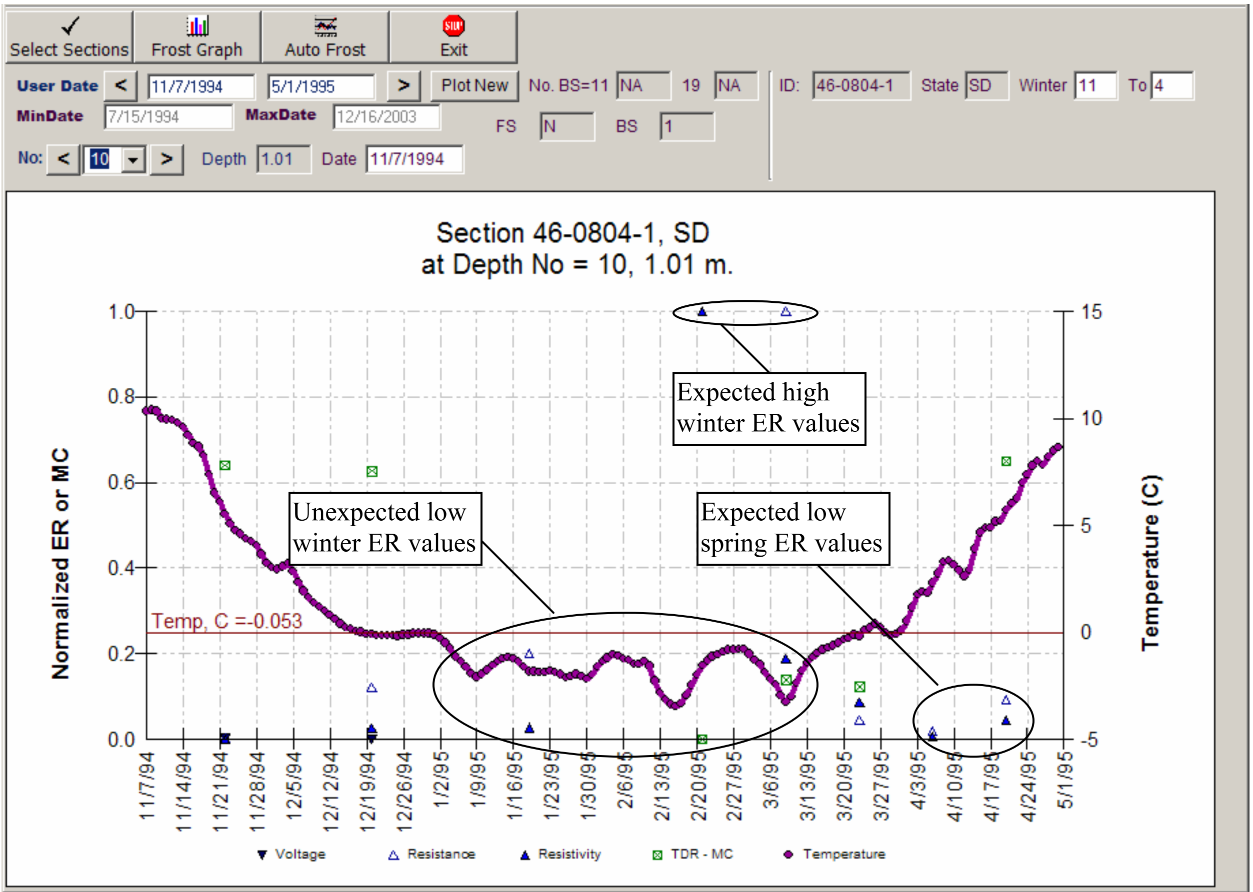


Figure 7. Chart. Comparison of ER, temperature, and moisture trends for section 0804 in South Dakota at 1.01 m (3.31 ft) depth.

Noncontinuous Frost Regions

There were eight sites with noncontinuous frost regions found in the LTPP database during the data review task. Each case with noncontinuous frost regions was reviewed. The following reasons were found that might have affected judgment when assigning noncontinuous frost regions:

- Missing subsurface temperature— decisions were based solely on ER measurements.
- Subsurface temperatures close to 0 °C—soil may be in a transition state.
- Drop in ER values relative to surrounding dates—sometimes ER values drop even when surrounding temperatures remain below freezing.

In all cases, assignments of freeze or no freeze conditions were highly subjective. Other noncontinuous frost layers could form as a result of thawing and refreezing of the top layers while a deep frozen layer remained in place until the end of the freezing period. Identifying areas of noncontinuous frost regions is difficult using either ER or temperature data. ER measurements can be ambiguous at the freezing isotherm. Temperature data are not adequate to identify noncontinuous frost regions because nonfrozen water between two frozen zones would be very near to 0 °C.

To remove some subjectivity in these assignments, moisture content analysis could be added to the frost analysis algorithm.

LTPP DATA REVIEW CONCLUSIONS

Two conclusions have been drawn from reviewing the existing LTPP frost data. The first conclusion is that the previous values for SMP_FREEZE_STATE and SMP_FROST_PENETRATION are not describing the actual freeze conditions in the subsurface layers accurately. This conclusion is primarily derived from examining the previously derived LTPP frost data. The reasons are as follows:

- ER measurements for SMP I and SMP II noncontinuous sites are sparse and do not provide enough data to determine the length of the freeze period or freezing-thawing changes that take place during the winter season.
- In some cases, ER data are erratic and counterintuitive (high values in summer and low in winter or high/low values in one of three collected ER values).
- The existing interpretation methodology does not utilize changes in moisture content.
- Frost predictions were made only for the dates with ER data; dates with subsurface temperatures below freezing were not included in the analysis if ER measurements were not obtained on the same dates.
- Many difficulties arise in determining freeze conditions around the freezing isotherm when soil transitions between freeze and no-freeze states.

The second conclusion is that a more accurate determination of the freeze state of the soil is possible by using subsurface temperature and moisture data in addition to ER measurements more extensively and by incorporating thermodynamic modeling to fill the gaps in measured temperature data. Thermodynamic modeling also could be useful for analyzing heat and moisture transfer processes that take place in subsurface layers, as well as assisting the analyst with frost predictions.

CHAPTER 3. REVIEW OF ADVANCES IN THE STATE OF KNOWLEDGE IN FROST PENETRATION ANALYSIS

Relevant literature was reviewed during Phase I of the project and is summarized in this chapter. The review included several published documents. (See references 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21.)

To improve the accuracy of frost predictions for the instrumented LTPP sections, alternative approaches to detection of frost in unbound pavement layers were investigated, including thermodynamic modeling of time-based changes in subsurface temperatures and changes in TDR traces.

The key outcomes of this background review included the following recommendations to improve the accuracy of frost predictions for the instrumented LTPP sections:

- Enhance current frost penetration methodology and accompanying FROST interactive program by integrating in-situ moisture content data from TDR measurements in frost penetration prediction and cross-reference changes in temperature, ER, and moisture to determine freeze state.
- Place more emphasis on analysis subsurface temperatures as these data were found to be most complete and reliable when comparing to ER and moisture data from SMP sections.
- Use thermodynamic modeling integrated into EICM to fill the gaps in measured subsurface temperatures.

Details are discussed in the following sections.

IN-SITU MOISTURE CONTENT FROM TDR MEASUREMENTS

Another viable method to identify frost regions is to use TDR data to identify the presence of ice by a decrease in moisture content when the soil is frozen. This method is detailed by Benson and Bosscher.[13]

Moisture content in the unbound pavement layers and subgrade soil affects frost severity due to the physical phenomenon of moisture migration in response to freezing. Even when the temperatures fall below the freezing point of the contained water, frozen soil may contain both frozen and unfrozen water in varying proportions depending on temperature depression, specific surface area, and salt content. The presence of unfrozen water provides the opportunity for moisture to migrate vertically, resulting in formation and thickening of ice lenses. Ice lenses represent horizontal layers of solid ice that form below the ground surface, separating the soil above from the soil below to form noncontinuous frost regions. Ice lenses may damage the pavement structure due to the large vertical displacements known as frost heaves.[18] As the pore water freezes, the volumetric moisture content drops to a very low level wherever a frost condition exists and therefore serves as a cross-reference for frost depth analysis. (See references 15, 16, 17, 18, 19.)

Example Using Moisture Data in Frost Analysis

The following example shows how moisture content (MC) data can improve the accuracy of frost predictions. As shown in figure 8, the SMP section 1026 in Maine experienced several periods of freeze-thaw during the 1994–1995 winter season. Light blue indicates that most subsurface temperature readings were taken between 0 and -1 ^{o}C, making freeze state prediction using ER values very challenging. At this temperature range, pore water may or may not have enough energy loss to freeze. Plus, soil salinity may affect the actual freezing isotherm value and depress it below 0 ^{o}C.

ER measurements were taken on seven dates during that winter season, as shown in figure 9. On the same dates, TDR measurements were taken and moisture content was computed. Of the seven ER measurement dates, the freeze state of the soil was detected on only two dates (January and February measurements) based on the ER data. Based on the analysis of moisture content fluctuations, an additional measurement on March 6, 1995, indicated that the soil was in a frozen state. This date has corresponding low moisture content and subzero temperature values. A summary of freeze state determination using different data sources is shown in table 2.

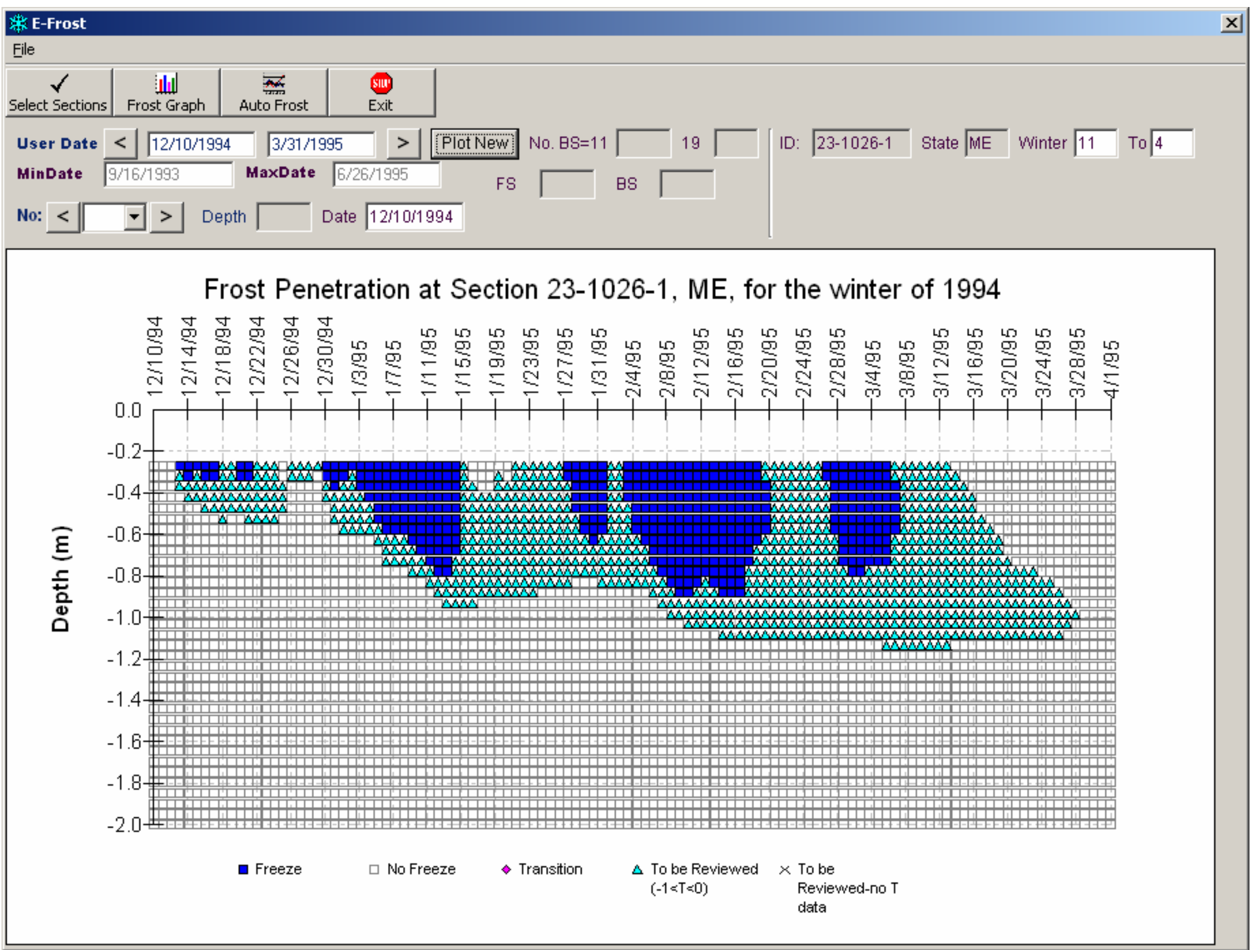


Figure 8. Chart. Frost predictions for section 1026 in Maine.

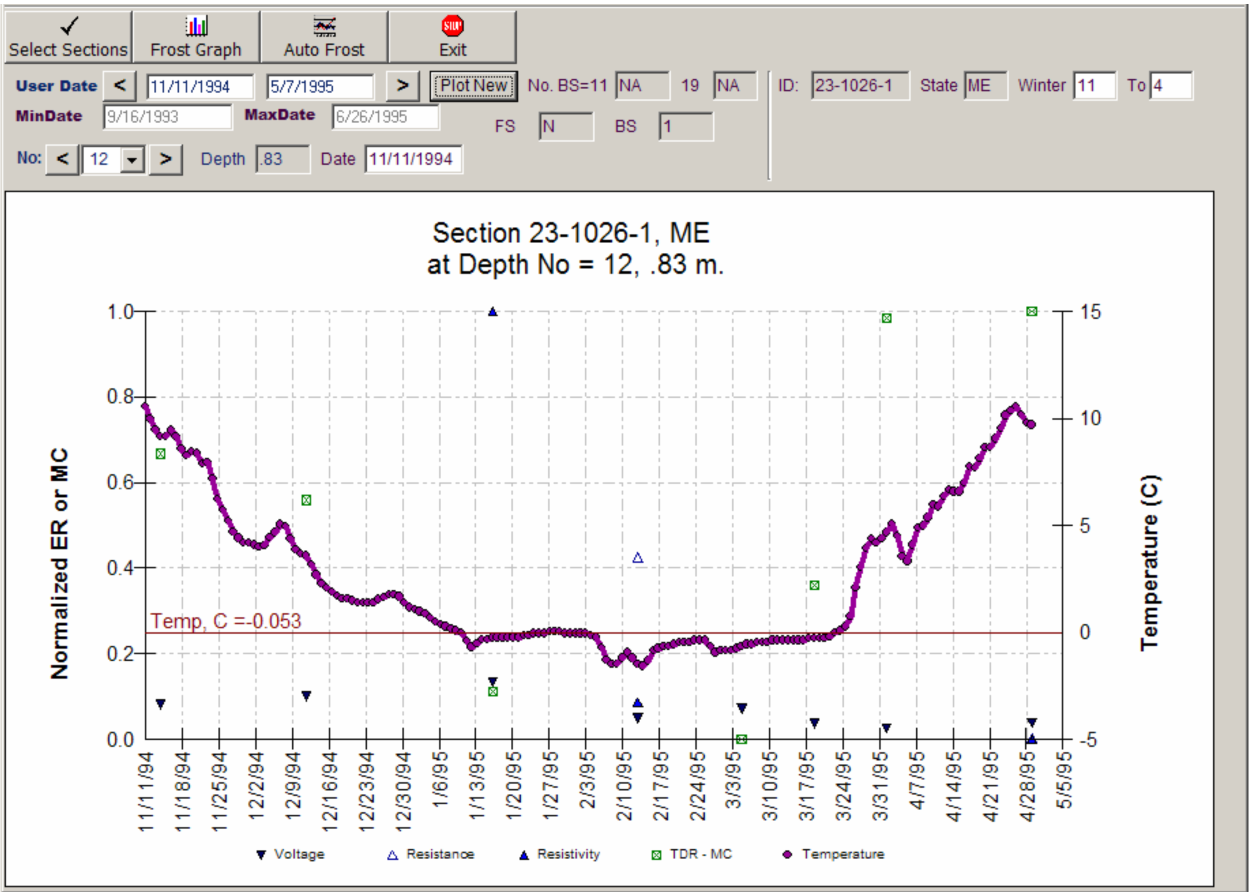


Figure 9. Chart. Comparison of ER, temperature and moisture trends for section 1026 in Maine.

Table 2. Freeze state evaluations using different data sources.

Date:	11/14/94	12/12/94	1/17/95	2/14/95	3/6/95	3/20/95	4/3/95	5/1/95
ER:	NF	NF	F	F	NF	NF	NF	NF
MC:	NF	NF	F	N/A	F	F/TR	NF	NF
T:	NF	NF	TR	F	F	TR	NF	NF

ENHANCED INTEGRATED CLIMATIC MODEL

The Integrated Climatic Model (ICM) was developed in the late 1980s to simulate temporal variations in the temperature, moisture, and freeze-thaw conditions internal to the pavement and their impact on key pavement material properties.[(14)] In FHWA-HRT-04-079,[(17)] this program was recognized as the most comprehensive model addressing the effects of climate on pavements. As its name suggests, the EICM is an enhanced version of the ICM. It was used as the basis for considering seasonal variations in the Mechanistic-Empirical Pavement Design Guide (M-E PDG).

The EICM consists of three models addressing different aspects of climatic effects on the pavement:

- Climatic-Materials-Structures (CMS) model, developed at the University of Illinois.[19]
- Infiltration and Drainage (ID) model, developed at the Texas Transportation Institute.[20]
- Frost Heave and Thaw Settlement Model, developed by the CRREL.[21]

The EICM provides the capability to simulate temperature, moisture, and freeze-thaw conditions internal to the pavement structure as a function of time. The accuracy of the predictions depends greatly on a proper selection of boundary conditions, climatic parameters, and material properties.

The EICM engages a coupled heat moisture finite element/difference model. It models heat flow by considering climatic and solar inputs at the surface along with the deep ground constant heat source. These thermal boundary conditions are used in conjunction with the moisture content of the subpavement soils to model heat flow, the freezing state of the soil, and frost penetration accurately. The model is coupled in the sense that changes in moisture content affect the thermal properties of the unbound layers—an increase in the moisture content increases the heat capacity and thermal conductivity of the material. Moisture content in the unbound layer is affected by the thermal conditions when freezing occurs. The drying process in the unbound layer causes moisture to move to the freezing zone.

This tool could be particularly useful for modeling subsurface temperatures when temperature data are not available for some dates or depths.

Example Using EICM Model to Predict Missing Temperature

The EICM analysis algorithm provides enhanced options to fill in the gaps in partial or incomplete measured subsurface temperature data, including a temperature auto-correction option. The analysis starts with inputting pavement and unbound layer data from the LTPP database and historical climate measurements into the EICM program. After the initial program run, the EICM temperature predictions are compared to the measured temperature data. The detailed examination of the measured and predicted data gives further guidance on how the inputs can be refined. For example, the unbound materials may model as being wetter or drier than the initial inputs suggest. Adjustments to the moisture content present in the profile can be achieved by varying inputs into the soil water characteristic curves (SWCC) of each unbound layer or by adjusting the depth of the water table. These small refinements can bring the predicted and measured values into agreement.

The auto-correction option is used to further improve predictions. Using this option, the temperature profile for each SMP site is modeled and calibrated against available partial field measured data on a daily basis, with the initial temperature profile being the previous day's temperature reading. For each time step where temperature is known, the measured value will supersede and overwrite the predicted temperature, causing the measured and predicted temperatures to track exactly in line with one another.

When measured data are missing for a time period, the EICM model will start in perfect agreement with measured data at the beginning of the time period. As the model steps through time increments, it no longer has measured data to correct to, and the predicted output represents the only understanding of what the temperature is. However, because of the agreement that was achieved in the initial modeling and accurate initial profile (corrected by the measured data), the EICM is capable of accurately bridging short gaps in the data. When measured data are once again available, it is possible to observe the error in the prediction and again correct the predicted data with LTPP measured data. Figure 10 illustrates the comparison between the model predictions and the LTPP field data before auto-calibration, and figure 11 illustrates the comparison after auto-correction calibration.

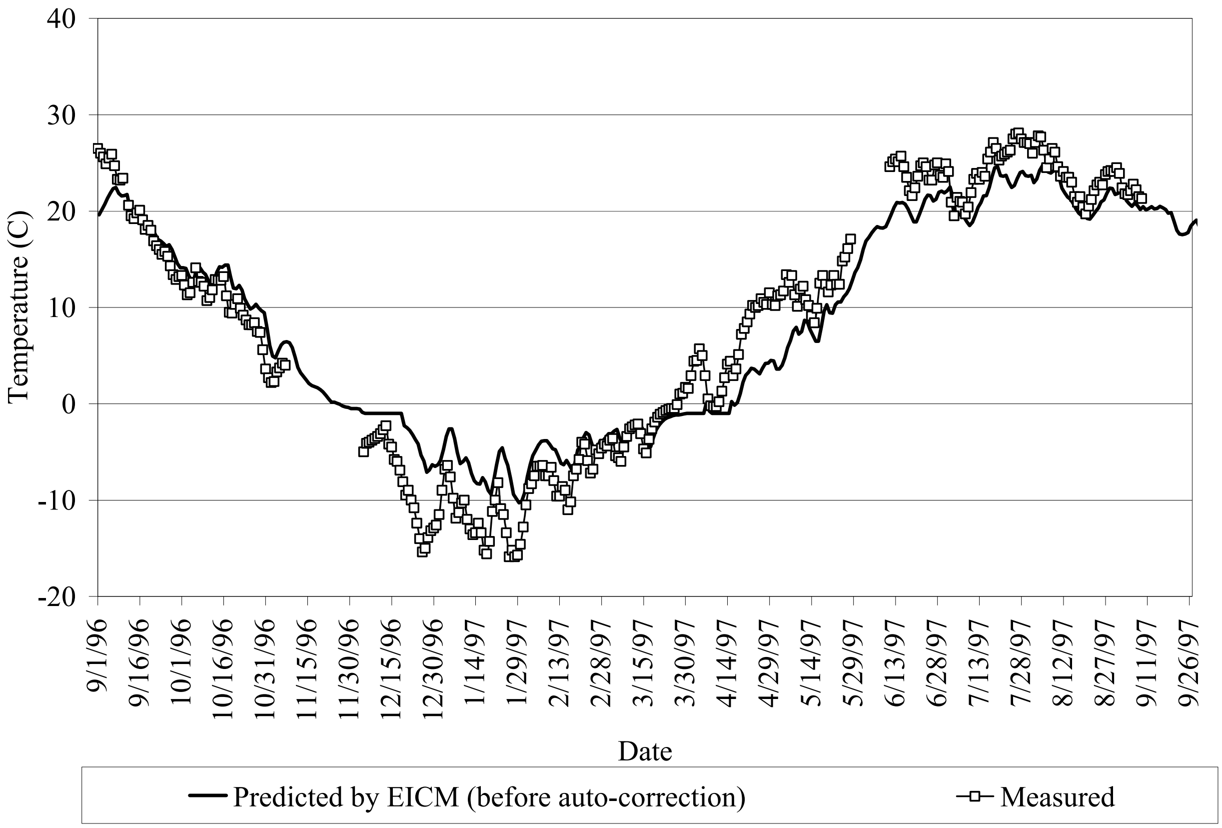


Figure 10. Chart. Measured and EICM predicted temperatures for section 6251 in Minnesota at 0.8 m (2.6 ft) depth before auto-correction.

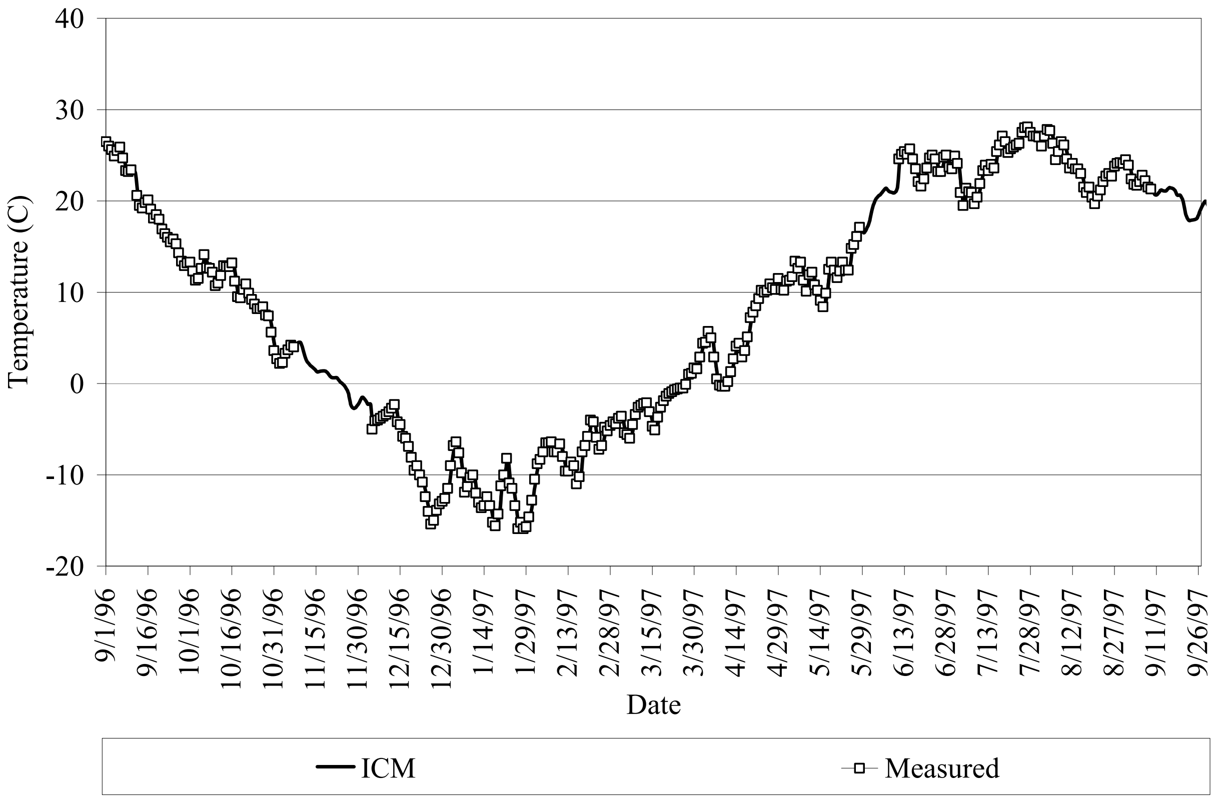


Figure 11. Chart. Measured and EICM predicted temperatures for section 6251 in Minnesota at 0.8 m (2.6 ft) depth after auto-correction.

CHAPTER 4. ENHANCED METHODOLOGY FOR LTPP FROST DETERMINATION

OVERVIEW

The following outline the basis of the enhanced LTPP frost penetration methodology:

- Include all three subsurface measurements (temperature, moisture, and electrical resistivity) collected by LTPP SMP program in freeze state determination.
- Place more emphasis on using subsurface temperatures for prediction of frost penetration, as these LTPP data were found to be the most complete, consistent, and reliable.
- Use the freezing isotherm as a threshold value to determine freeze or no-freeze state of the unbound materials.
- Use analysis of moisture and electrical resistivity trends for temperatures close to the freezing isotherm value, where available, to evaluate temperature-based frost predictions and make corrections as necessary.
- Use thermodynamic modeling to predict missing temperatures and to gain insights into the heat exchange processes in the unbound layers to aid in frost penetration determination.

DETERMINATION OF FREEZING ISOTHERM

In the LTPP frost penetration analysis, the freezing isotherm was used to define a threshold temperature value differentiating between the freeze and no-freeze states of unbound pavement layers. The official definition of frost condition provided by the National Snow and Ice Data Center (NSIDC) is the condition which exists when the temperature of earth-bound objects falls below freezing (0 ^{o}C or 32 ^{o}F) (http://nsidc.org/cgi-in/words/letter.pl?F). However, based on the soil type and salinity, this temperature could have been depressed below 0 ^{o}C, making frost determination based on temperature alone questionable at low-freezing temperatures (0 ^{o} to -1 ^{o}C). In such circumstances, changes in moisture and ER values were used to aid in freeze state determination. As soil temperature crosses over the freezing isotherm value, the following changes in moisture and ER values are expected:

- Transition from a no-freeze to freeze state—sharp decrease in moisture at the end of transitional period in wet soils. ER values are low before the beginning of freezing and high once the complete freeze occurs; ER readings can be ambiguous during the transition period. Temperature drops below 0 ^{o}C at the end of transition.
- Transition from freeze to no-freeze state—increase in the moisture and sharp decrease in ER values at the end of the freezing period. Temperature rises above 0^{o}C at the end of transition.

Close examination of the LTPP data showed that no sites had strong or consistent evidence of the freezing isotherm being depressed below -1 ^{o}C. Based on these observations and considering the NSIDC frost definition presented at the beginning of this section, 0 ^{o}C was chosen as a default freezing isotherm for the analysis.

To account for the possibility that the freezing isotherm could be below 0 ^{o}C, a step was added to the analysis procedure that required a manual review and assignment of a freeze state based on conclusions from temperature, ER, and moisture trends analyses for the periods of time with temperatures between 0 ^{o} and -1 ^{o}C. This provision allowed assignment of no-freeze or transitional conditions even when temperatures were below 0 ^{o}C.

DETERMINATION OF FREEZE STATE

Freeze-Thaw Processes

Frost forms in unbound pavement layers and subgrade when moisture is present in the soil and the temperature of the soil matrix falls below the freezing point of the contained water. When soil undergoes freezing or thawing, temperature stays constant at about the freezing/thawing point until the entire body of water is completely frozen or thawed. This physical process is known as the latent heat of fusion. The length of the constant temperature period varies with soil type, the amount of moisture in the soil, and the rate of change in air temperature. More saturated soils take longer to freeze. Granular materials are more likely to have a distinct freezing temperature, while fine-grained soils can have a considerable freezing range over which the soil water freezes.

In the spring, sunshine and warm air temperatures result in a top-down thawing of the pavement system. The water released by the melting ice can be trapped by deeper, still frozen material, creating saturated or supersaturated conditions that weaken the pavement structure. The thawing process can take from several weeks to several months, depending on the type of soil and the ease with which the excess water can drain back to the water table.

Freeze State Assignment

Close examination of daily thermistor readings in conjunction with the observation of ER and moisture trends were used to determine the freeze state of the unbound materials. The first-order approximation of the freeze state of the soil was determined by analyzing changes in subsurface temperatures with respect to the 0 °C freezing isotherm. For each site with subsurface temperature measurements, a frozen state of the soil was assigned for dates and depths with temperatures below 0 °C freezing isotherm. A no-freeze state was assigned to the soil for dates and depths with temperatures above 0 °C freezing isotherm.

Following this initial freeze state assignment, a more detailed analysis was conducted for the dates and depths with temperatures that fell in the range 0 ° to -1 °C. In this analysis, in addition to temperature readings, changes in ER and moisture values were analyzed over time and through the depths to determine the freeze state of the soil. If analysis of ER and moisture trends did not provide evidence supporting either transitional or no-freeze state, the freeze state previously assigned using the 0 °C freezing isotherm was not changed; otherwise, a new freeze state was assigned. Table 3 provides a summary of expected trends in temperature, moisture, and ER measurements to support assignment of different freeze state conditions.

Table 3. Freeze state characteristics.

Soil freeze state	ER trend	TDR trend	Temperature trend	Characterized by physical process
Frozen	High	Low	Below freezing isotherm	Pore water is solid frozen. Ice lenses formed in frost-heave susceptible soils
Unfrozen	Low	High	Above freezing isotherm or above 0 °C	Pore water is in a liquid state
Transitional	Unstable	Rapid change	Around freezing isotherm	Pore water is transitioning between liquid and solid state or partially frozen

Due to a limited availability of ER and moisture data for the dates of interest and sometimes due to inconclusive or unexplained ER and moisture trends, only a limited number of sites had the results of temperature-based freeze state prediction changed based on ER and moisture trend analysis, resulting in a limited number of transitional and no-freeze state assignments reported for temperatures at or below 0 °C.

In addition, for some of the SMP I sites that had ER data available but no measured or predicted temperature and moisture data, freeze states were established based on the analysis of seasonal changes in ER trends. Freeze states were determined for the dates that corresponded to the historical winter months and had high ER values on a scale normalized from 0 to 1.

THERMODYNAMIC MODELING OF SUBSURFACE TEMPERATURES

Thermodynamic modeling of the pavement structure was included in the LTPP frost penetration analysis for two reasons. First, it provided means for small amounts of missing subsurface temperature data to be accurately interpolated from the measured data. Second, thermodynamic modeling based on measured temperatures was used to aid in understanding the physical processes that took place in the field.

Thermodynamic modeling of the pavement structure was accomplished using EICM. The EICM's temperature auto-correction option was used in the analysis of LTPP data. Using this option, the EICM-predicted temperature values for each day were auto-corrected based on actual measured thermistor readings. The temperature profile for each SMP site was modeled on a daily basis, with the initial temperature profile being the previous day's temperature reading. If there were measured data for the following day, the EICM prediction were ignored. If measured temperature data were missing for the following day, temperature predictions considering all of the required inputs were made.

Prior to this daily auto-correction, the site was modeled and the inputs were calibrated to give an accurate set of predictions using the following procedure:

1. Select model inputs for a specific site from the LTPP construction history, materials, and testing tables, along with the collected climatic data.
2. Run the model.
3. Compare these predictions to the actual measured values.

4. Calibrate the model by varying the initial parameters so that the EICM predicted temperature profile exactly matches the known measured profile.

The secondary use of the EICM was to ensure that basic thermodynamic behavior was not violated in the course of determining frozen and thawed zones within the structure. For example, it is practically impossible for a soil to freeze to a depth of 2 m (6.56 ft) over a 24-hour period. The amount of heat released from freezing such a large quantity of water could not escape from the pavement or ground.

Cautionary Note

The thermodynamic modeling of subsurface pavement and soil layers can be an inexact science. Nonuniformity of materials, variable ground water tables, and other poorly defined inputs can cause considerable divergence between actual and predicted values. Careful modeling and selection of appropriate defaults can appreciably increase the prediction accuracy of thermodynamic programs but still will not yield accurate predictions for all cases. The auto-correction process is tedious and is based on the subjective analyst's judgment in selection of unknown input parameters. Furthermore, the EICM requires an extensive list of site-specific inputs. Not all of the required input parameters were available in the LTPP database, and those that were available were not available for all SMP sites.

LTPP FROST PENETRATION ANALYSIS PROCEDURE

The flowchart in figure 12 shows the step-by-step process used to determine freeze state and layers for unbound pavement layers and subgrade for each LTPP site included in this study.

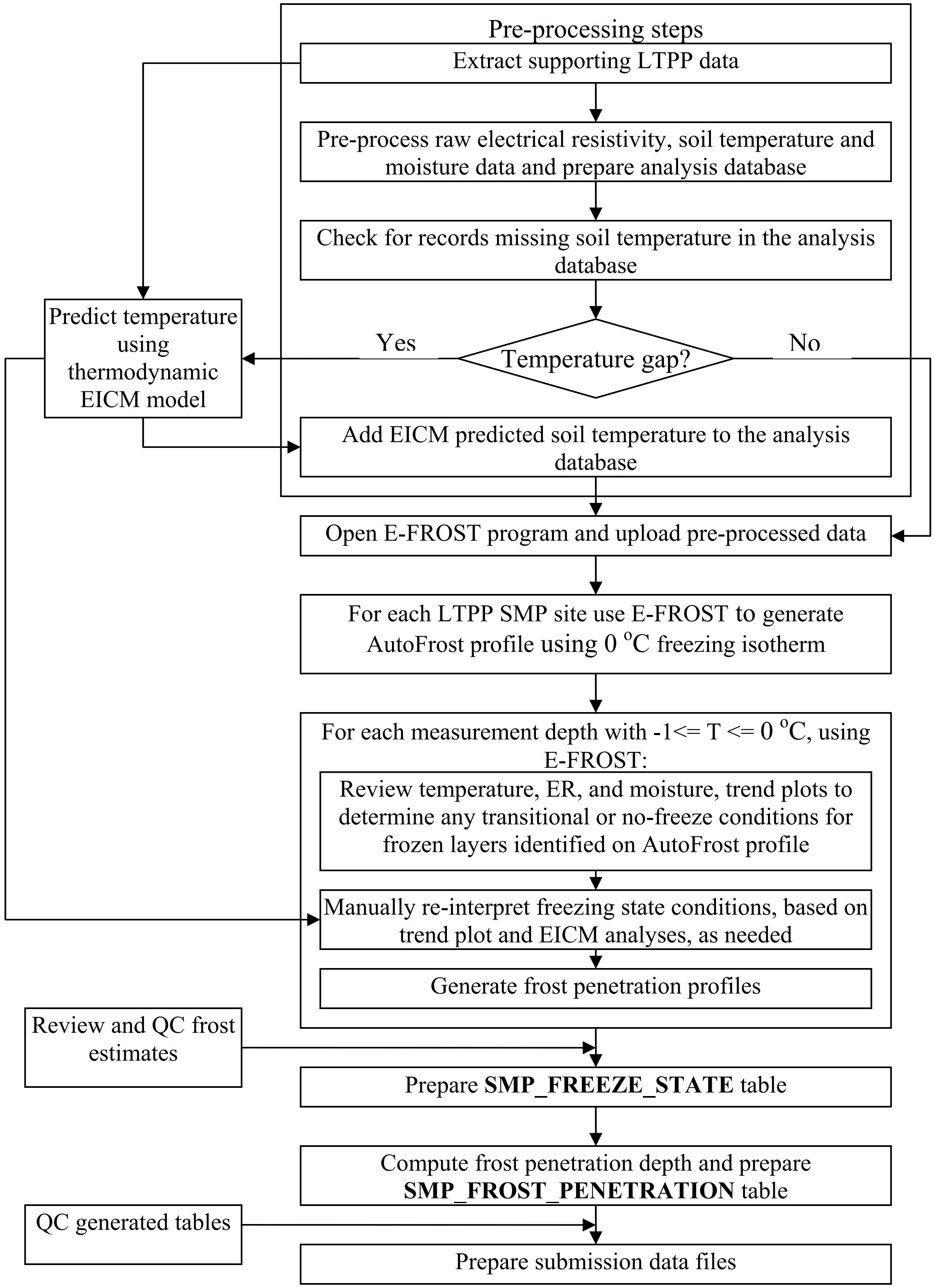


Figure 12. Chart. Frost depth and layers interpretation using E-FROST.

Additional Analysis Rules

Upon a detailed data review, it became apparent that not all of the data were available for every measurement date and depth, and some of the trends based on the in-situ data were difficult to interpret, leading to subjectivity in assignment of freeze states by the analyst. To minimize the subjectivity of the frost estimates and to provide uniformity of the analysis procedures, a set of guidelines was developed and followed by the data analyst.

During the data analysis phase, the following rules were followed when data were sparse or some of the measurements were ambiguous:

1. For each date and measurement depth that had at least subsurface temperature or ER data available, freeze state estimates were conducted using methodology presented earlier in the report.
2. If subsurface temperature measurements and ER data were missing for a portion of the winter season and there were sufficient LTPP data to estimate missing temperatures from EICM analysis, these estimated temperatures were used to evaluate freeze state. The source of the temperature in the SMP_FREEZE_STATE table was specified as estimated from EICM.
3. For measurement depths and/or dates where no in-situ data and no EICM-predicted temperature values were available to predict the freeze state, no freeze state determinations were made, even though frozen depths were reported for surrounding depths and/or dates.
4. For some SMP I sites that had ER data available but no measured or predicted temperature and moisture data, freeze states were determined based on the analysis of seasonal changes in ER trends. Freeze states were determined for the dates that corresponded to the historical winter months and have high ER values on normalized scale from 0 to 1.
5. If, for a particular date and depth, the soil temperature was above 0 ^{o}C, the freeze state was reported as N-unfrozen.
6. If, for a particular date and depth, the soil temperature was below -1 ^{o}C, the freeze state was reported as F-frozen.
7. If, for a particular date and depth, the soil temperature was below 0 ^{o}C, the moisture values were low, and ER values were high, the freeze state was reported as F-frozen.
8. If, for a particular date and depth, the soil temperature was below 0 ^{o}C, the moisture values were low, and no ER values were reported, the freeze state was reported as F-frozen.
9. If, for a particular date and depth, the soil temperature was below 0 ^{o}C, the ER values were high, and no moisture values were reported, the freeze state was reported as F-frozen.
10. In the absence of moisture and ER data or when ER and moisture trends are inconclusive, the freeze state was reported as F-frozen for temperatures less or equal 0 ^{o}C.

11. If, for a particular depth, constant negative temperatures near 0 ^{o}C were observed over a few days, the freeze state was reported as T-transition and the following trends arose:
    - Constant negative temperature near 0 ^{o}C over a few days + continuous rapid increase in moisture + low ER at the end of transition (thawing process).
    - Constant negative temperature near 0 ^{o}C over a few days + continuous rapid decrease in moisture + high ER at the end of transition (freezing process).
    - Constant negative temperature near 0 ^{o}C over a few days + continuous rapid increase in moisture, No or ambiguous ER data (thawing process).
    - Constant negative temperature near 0 ^{o}C over a few days + continuous rapid decrease in moisture, No or ambiguous ER data (freezing process).

Data Normalization and Interpolation

To aid in the visual interpretation of the analysis results, electrical resistivity values were normalized on a scale from 0 to 1. Normalization was carried out for each analysis depth and construction event, which was identified by the change in the construction number. The following basic normalization formula was utilized:

$$Normalized\_Measurement = \frac{Actual\_Measurement\text{-}Min\_Of\_Actual\_Measurement}{Max\_Of\_Actual\_Measurement\text{-}Min\_Of\_Actual\_Measurement}$$

Figure 13. Equation. Normalized measurement.

Where:

Normalized_Measurement	=	Normalized measurement
Actual_Measurement	=	Actual measurement
Min_Of_Actual_Measurement	=	Minimum actual measurement
Max_Of_Actual_Measurement	=	Maximum actual measurement

Extracted LTPP temperature and moisture content data were interpolated to ER analysis depths established in earlier LTPP frost penetration studies[3] using the following linear interpolation formula:

$$Interpolated\_Measurement = Upper\_Measurement + (Lower\_Measurement - Upper\_Measurement)\frac{X}{L}$$

Figure 14. Equation. Interpolated measurement.

Where:

Interpolated_Measurement	=	Interpolated temperature or MC value
Upper_Measurement	=	Temperature at upper thermistor or MC for upper TDR sensor
Lower_Measurement	=	Temperature at lower thermistor or MC for lower TDR sensor

X = Distance from the ER analysis depth to the upper thermistor or TDR sensor
L = Distance between the two thermistors or TDR sensors

QUALITY CONTROL/QUALITY ASSURANCE PROCESS

The results of data analysis were independently reviewed. During the review process, emphasis was placed on evaluating whether or not the results produced by the analyst followed the basic physical process of latent heat of fusion as described earlier in this chapter. In addition to reviewing the frost penetration profiles, trends in temperature, ER, and moisture changes were reviewed and correlated to evaluate the accuracy of analyst assigned freeze states.

Spatial and Temporal Checks

Frost penetration profiles were reviewed to evaluate the progression of frost penetration with time and depth and to check for any potential data gaps or presence of intermediate unfrozen layers. The following two checks were used to QC the initial freeze state assignments for all the cells in frost penetration plot except the boundary cells (boundary cells belong to the first frozen depth layer, the last frozen depth layer, the first and the last date with frost for each depth)**:**

Spatial check for a given date is as follows:

- If a layer above (= depth i-1) was determined as frozen, a layer below (= depth i+1) was determined as frozen, and the temperature remained <= 0 ^{o}C, then the layer in between (= depth i) is likely to be frozen and should be assigned as freeze.
- If a layer above was determined as no-freeze (= depth i-1), a layer below (= depth i+1) was determined as no-freeze, and the temperature remained near 0 ^{o}C, then the layer in between (= depth i) is likely to be no-freeze and should be assigned as no-freeze.

Temporal check for a given depth is as follows:

- If the freeze state for a date before was determined as frozen, the freeze state for a date after was determined as frozen, and the temperature remained <= 0 ^{o}C for all three dates, then the freeze state for the date in between is likely to be frozen and should be assigned as freeze.
- If the freeze state for a date before was determined as no-freeze, the freeze state for a date after was determined as no-freeze, and the temperature remained near 0 ^{o}C for all dates, then the freeze state for the date in between is likely to be no-freeze and should be assigned as no-freeze.

Trend Reasonableness Check

ER, moisture, and temperature time-series plots were reviewed to evaluate reasonableness of ER and moisture changes with respect to temperature changes. The expected trends for ER and moisture changes are described as follows:

- Moisture: Expect to see a drop in moisture at the beginning of freeze period, as temperatures drop below 0 ^{o}C; low moisture values during frozen period; and rise in moisture during thawing, as temperatures climb above 0 ^{o}C.
- ER: Expect to see rise in ER at the beginning of freeze period, as temperatures drop below 0 ^{o}C; high ER values during freeze period; and drop in ER during spring thaw, as temperatures climb above 0 ^{o}C.

If and when the moisture and/or ER trends did not follow the expected trends described above, freeze assignment was based on temperature values with 0 ^{o}C used as freezing isotherm.

Analysis Results Database Checks

Finally, the results of the analysis compiled in the LTPP computed parameter tables were reviewed to assure data completeness, data integrity, and proper formatting.

CHAPTER 5. IMPLEMENTATION OF THE ENHANCED FROST ANALYSIS METHODOLOGY

UPDATES TO FROST PROGRAM

Using the data analysis methodology presented in chapter 4, the existing FROST interactive procedure was updated to enhance the analysis algorithm, to address changes from SMP II experiment, and to assure compatibility with current database technology. The updated supporting research tool was named E-FROST to differentiate with the previous version.

E-FROST Overview

The E-FROST research tool was developed to aid the data analyst in reviewing LTPP SMP data (temperature, ER, and moisture) and assigning freeze states based on the observed data trends. The primary functions of E-FROST are (1) to show time-series data from the in-situ measurements (ER, temperature, and moisture), (2) to generate and graphically represent frost penetration profiles, and (3) to create a frost penetration table containing frost penetration depths for different dates for which in-situ measurements were taken. The E-FROST user's guide with detailed instructions and examples is provided in appendix A.

Enhancements to LTPP Frost Interactive Procedure

Several improvements were made to the existing FROST interactive procedure to help determine the freeze state. To improve accuracy in frost penetration predictions in subsurface layers, the FROST algorithm was modified to include all available temperature, moisture, and ER data in the frost penetration analysis. The E-FROST graphic user interface was updated to provide means for review of daily temperature, moisture, and ER data plotted on the same plot. This feature enables the analyst to conduct comprehensive trend analysis of changes in temperature, ER, and moisture data in order to determine the freeze state of the soil at any date and depth that had in-situ measurements collected by LTPP.

The AutoFrost option was added to generate the initial frost penetration profile based on subsurface temperature values. This feature uses an objective measure, such as temperature at water freezing point, as a threshold value to determine the initial frost penetration profile instead of an arbitrary threshold value selected by the analyst, as was used in the previous FROST algorithm.

The EICM software was used for thermodynamic modeling of temperature distribution in subsurface layers, as appropriate, to fill the gaps in the field data and to aid the analyst in the examination of heat transfer processes based on the in-situ temperature data for the site. EICM-estimated subsurface temperature data was included in the E-FROST database so that it can be displayed on the interactive trend plots for the sites with missing or limited measured temperature data.

Changes from SMP II Experiment

The original FROST program was developed to process data from the SMP I experiment. Introduction of the SMP II experiment led to the development of the new LTPP database tables to store ER data and resulted in a significant increase in the quantity of data to process for each site.

Introduction of the SMP II experiment also resulted in a different ER table structure and a significant increase of data to be processed for each SMP II site. E-FROST accounts for these changes. To cope with massive amounts of data, the program provides the analyst with options to review the data for the selected time intervals instead of displaying data for all dates on a single plot. The program routines and preprocessing database were updated to ensure database compatibility with Microsoft® Access 2000 or later, which is needed to facilitate preprocessing of the new SMP II data.

ENHANCED FROST ALGORITHM

The decision tree algorithm for the E-FROST program is presented in figure 15.

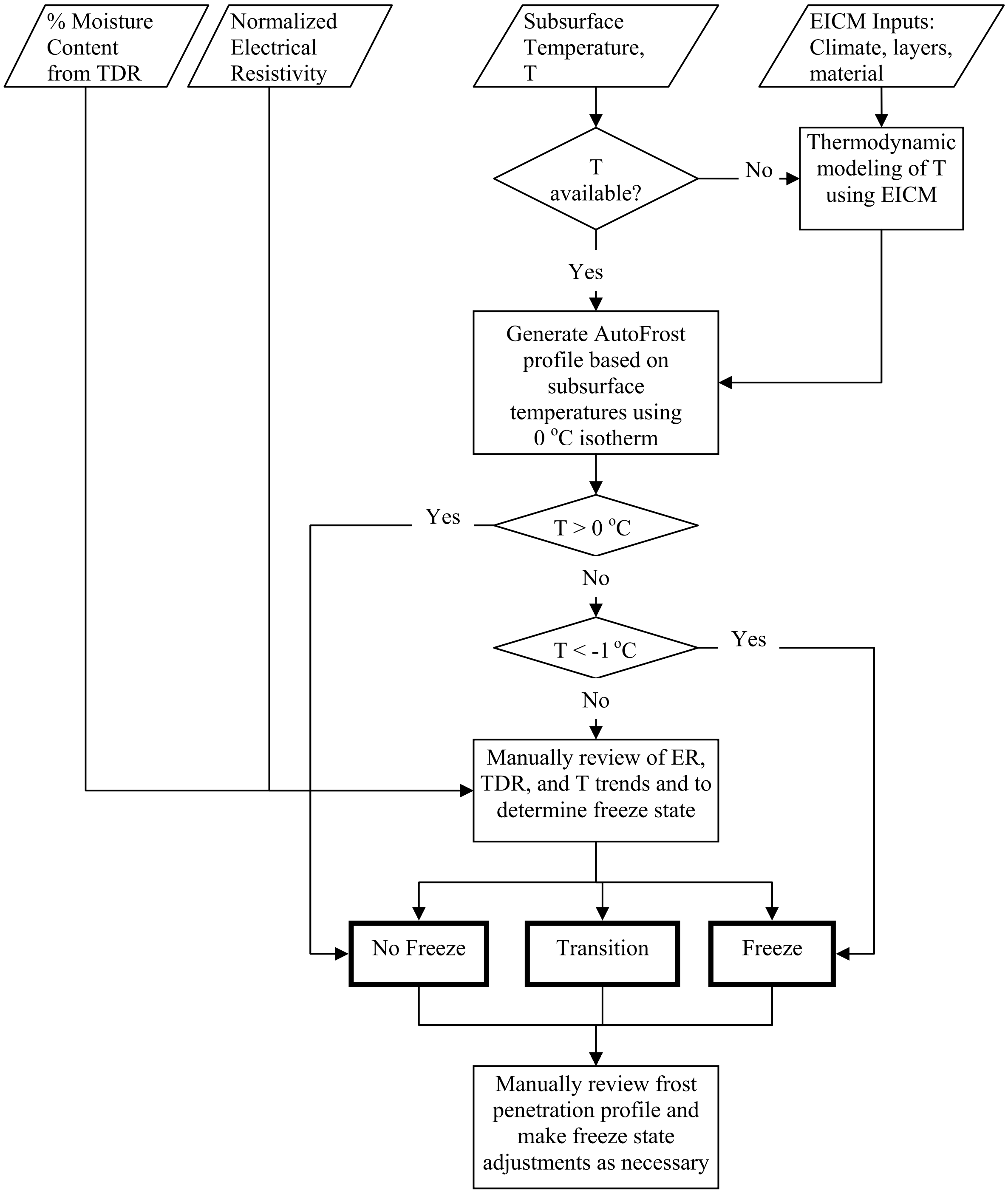


Figure 15. Chart. Enhanced FROST algorithm.

E-FROST Symbol Color Codes and Shapes for the Decision Tree

Upon execution, E-FROST creates a temperature-based first order approximation of frost penetration profile for each SMP site using the AutoFrost analysis option. The profile consists of a grid with the horizontal axis displaying different SMP dates on a daily scale and the vertical axis displaying different analysis depth based on ER probe depths. Each cell is color-coded to provide information about the freeze state at a given date and given depth (see table 4).

Table 4. Freeze state and frost depth chart symbol shape and color coding.

Color code	Symbol shape	Assigned freeze state	Subsurface temperature	Analyst's action
Blue	Rectangle	Freeze	T < -1 ^{o}C	Assigned automatically; however, the analyst has an option to change the state to transitional (pink) or no-freeze (white) upon data review
White	Rectangle	No freeze	T > 0 ^{o}C	Assigned automatically; however, the analyst has an option to change the state to transitional (pink) or freeze (blue) upon data review
Light blue	Triangle	Review	T < 0 ^{o}C and T > -1 ^{o}C	Assigned automatically; however, the action is required from analyst to manually review the data and change the state to freeze, no-freeze, or transitional
Pink	Diamond	Transitional	Near freezing isotherm	This color is assigned upon analyst review of all supporting data when it is not clear whether soil is frozen or not (partially frozen case)

The E-FROST algorithm automatically assigns the state of subsurface freeze condition at each electrode location using the following rules:

- The 0 ^{o}C freezing isotherm value is used as the low boundary to define the no-freeze state. No-freeze is automatically assigned to all points with temperatures above 0 ^{o}C (white cells).
- A value of -1 ^{o}C is used as an upper boundary to define the freeze state. Freeze is automatically assigned to all points with temperatures below -1 ^{o}C (blue cells).
- All data that fall between the two boundaries are flagged for manual review by the analyst to determine the appropriate freeze state based on ER, temperature, and moisture trend analysis (light blue triangles).

Based on the assigned freeze state, different actions will be required. No actions are required for blue or white cells. If E-FROST assigns the cell as "Review" (light blue triangle), the analyst must review the data and change the freeze state as appropriate. To aid in this decision, E-FROST creates a time-series plot of ER, temperature, and moisture content changes. The plot appears on the screen once the analyst clicks on the light blue triangle cell. Similar plots can be brought up for review by clicking on any other cell on the frost penetration profile chart.

FROST PENETRATION ANALYSIS EXAMPLE

The following example demonstrates the frost penetration analysis procedure to determine the freeze state and layers for unbound pavement layers and subgrade for LTPP site 0804 in South

Dakota. This site was chosen for the example because it contains the most comprehensive temperature, ER, and moisture data and provides means for cross-comparison of changes in all three measurement types. The plots provided in this example were generated using E-FROST.

Step 1. Prepare E-FROST Inputs Database

ER, temperature, and moisture content data were obtained from the LTPP tables, which are specified in chapter 6. When measured subsurface temperatures were not available, temperature values were estimated using the EICM thermodynamic model; EICM inputs are listed in appendix B. An example of how temperature gaps could be filled out by EICM predictions using the thermodynamic model was shown in figure 11 (chapter 3).

Extracted LTPP data were preprocessed to obtain normalized ER values at calculated analysis depths and to interpolate temperature and moisture content data to those depths. Preprocessed electrical resistivity, temperature, and moisture content data were assembled in the analysis database table required to run E-FROST.

Step 2. Generate an "AutoFrost" Freeze State Profile

An automatic frost penetration profile was generated based on thermistor readings with the 0 ^{o}C isotherm used as a threshold value to differentiate freeze states. In the example shown in figure 16, all data points with temperature readings above 0 ^{o}C are shown using white squares with grey borders. These data points correspond to no-freeze states. All data points with temperature readings below -1 ^{o}C are shown using blue squares. These data points correspond to freeze states. Data points with temperature readings between data 0 ^{o} and -1 ^{o}C are shown using light blue triangles. These data points require manual review, as they may represent a(n) frozen, unfrozen, or transitional state of soil.

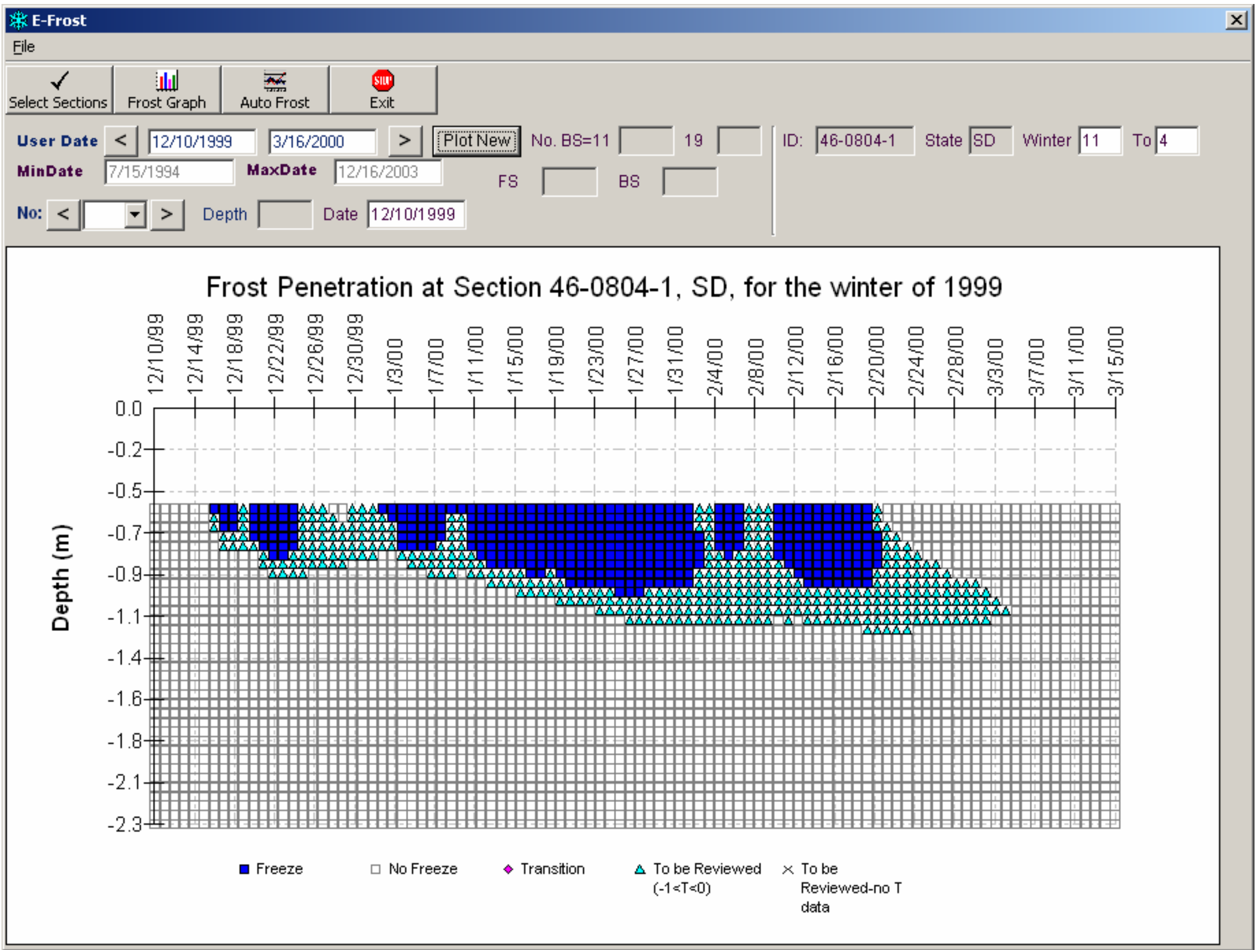


Figure 16. Chart. Example of temperature-based frost penetration profile for section 0804 in South Dakota.

Step 3. Review ER, Moisture, and Temperature Trends

Temperature, ER, and moisture content time-series trends were examined to verify the freeze state of soil assigned by the AutoFrost option, especially when temperatures were close to 0 ^{o}C. This was done by reviewing and correlating changes in temperature with changes in ER and moisture trends. E-FROST was used to graph temperature, ER, and moisture changes with time for each winter season and each measurement depth.

Upon data review, the state of soil was assigned to every date at every depth using trends described in table 3 as guidance. For the example shown in figure 17, the no-freeze state was assigned to dates prior to December 15 because the temperature readings, although close to 0 ^{o}C, never crossed the 0 axis. The state of the soil between December 16 and 24 was assigned as freeze as the data show a rapid drop in temperature values below 0 ^{o}C, followed by a decrease in moisture content. A transitional state of soil was assigned to December 25–27 and 30–31. Even though the temperature reading remained below 0 ^{o}C for these dates, there was a significant increase in moisture content, indicating thawing. The state of the soil for December 28 and 29 was assigned as no-freeze, as temperature values for these dates were above 0 ^{o}C. The state of the soil from January 1, 1999, to February 21, 2000, was assigned as freeze, as the trends in all three types of measurements (temperature, moisture, ER) indicated the possibility of frost—sharp decrease in moisture, sharp increase in ER, and temperature drop below 0 °C. For February 22, 2000, the no-freeze state was assigned based on observed trends in all three measurements: temperature rapidly rising above 0 °C, sharp decrease in ER, and sharp increase in moisture.

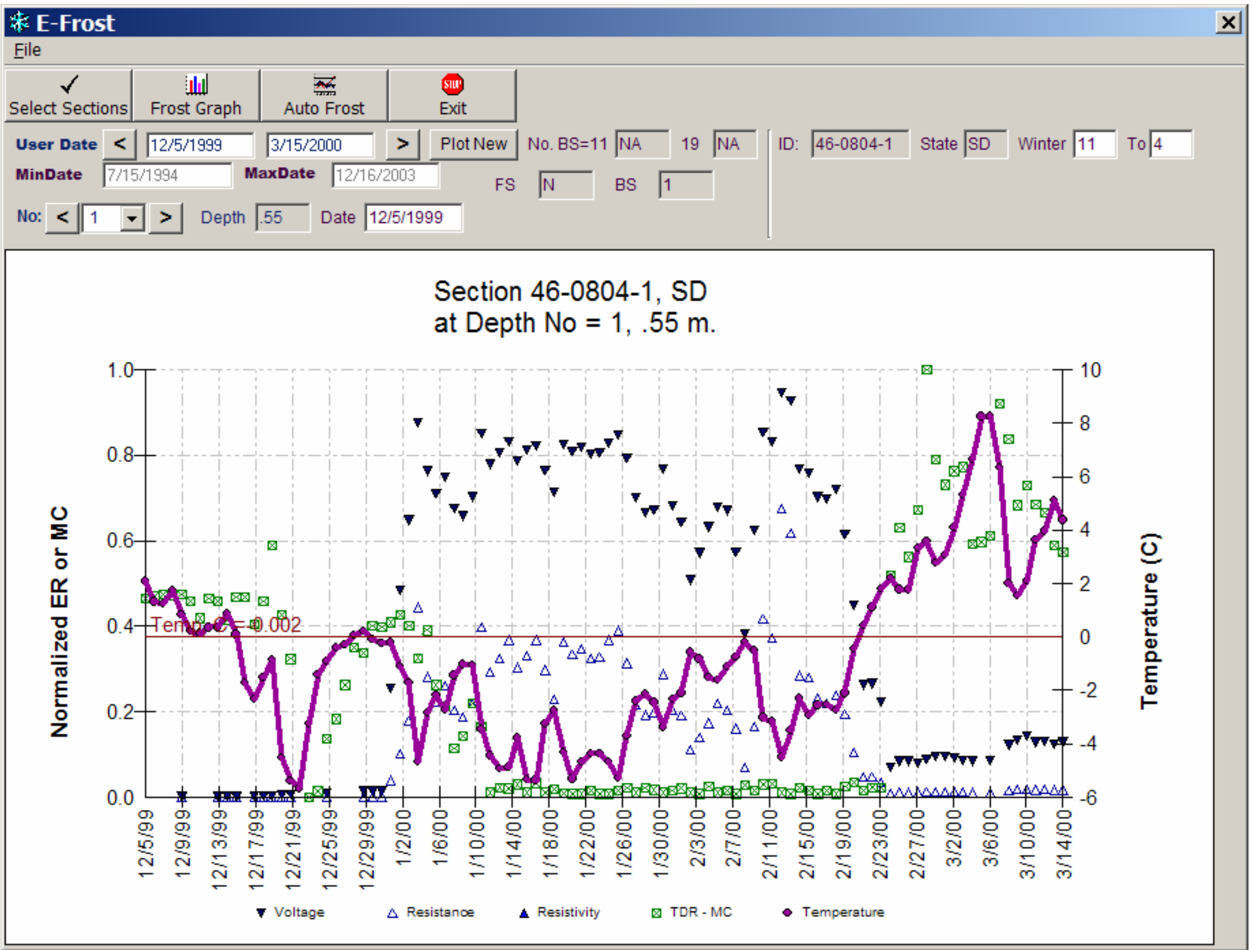


Figure 17. Chart. Example of ER, temperature, and moisture trends for section 0804 in South Dakota at 0.55 m (1.8 ft) depth.

Step 4. Generate and Review Frost Penetration Profile

Upon the completion of trend analysis at each of the 35 measurement depths and assignment of freeze states by the analyst, the E-FROST algorithm displays color-coded frost penetration profiles for review and quality assurance, as shown in figure 18.

Because of many less-than-ideal scenarios in the field data, the data interpretation process can be subjective. If the freezing condition at a particular point is in disagreement with the surrounding points (e.g., the point shows freezing while the soil above and below shows a no-freeze state), then the freeze state of that point may be changed by the analyst or QA reviewer to agree with that of the surrounding soil.

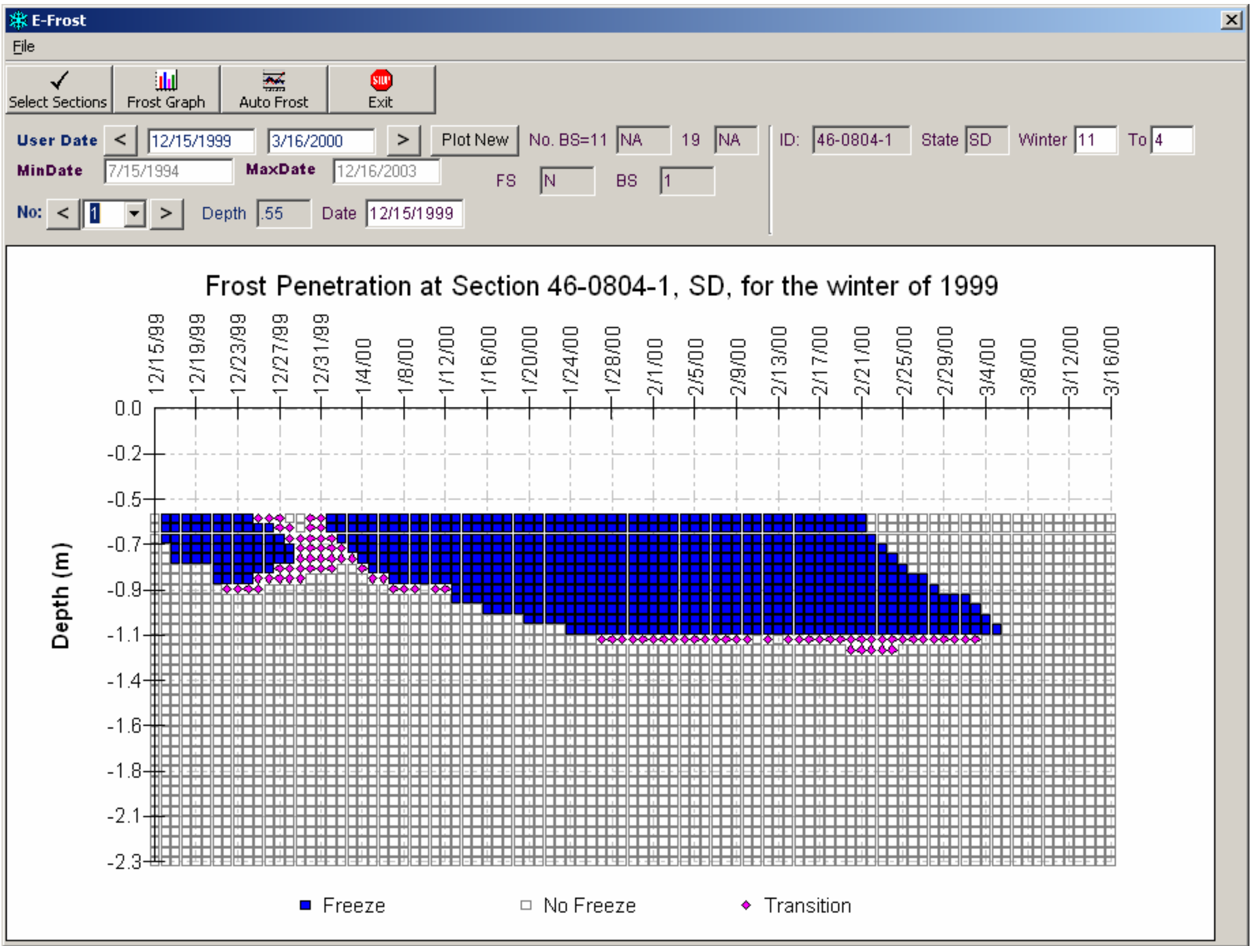


Figure 18. Chart. Example of final frost penetration profile for SMP site 46-0804 for the winter of 1999.

Step 5. Calculate Frost Depth Using Freeze State Information

Using freeze state information at each measurement depth, frost depths were computed for each date using E-FROST. Frost depth calculations were based on the interpreted freeze states (F-frozen and T-transitional or partially frozen).

For each date, frost depths were computed based on the interpreted freeze states (F-frozen and T-transitional or partially frozen) using the following algorithm:

- Starting (top) depth of a frozen layer was determined as the first measurement depth from the pavement surface where “F” freeze state was determined on frost penetration plot (shown in figure 18).
- Ending (bottom) depth of a frozen layer was determined as the last measurement depth from the pavement surface where “F” freeze state was determined on frost penetration plot.
- If, for a given date, a no-freeze state “N” was found within the vertical array of freeze states “F”, then multiple freeze layers were reported for that date. In these cases, the

bottom of the first frozen layer was determined as the last measurement depth with freeze state “F” before the intermediate no-freeze ”N” layer. The top of the second frozen layer was determined as the first measurement depths with freeze states “F” after the intermediate no-freeze ”N” layer.

- No frozen depths or layers were estimated for depths and dates without measured temperature and ER data.

Freeze state information was added to SMP_FREEZE_STATE, and frost depth information was added to the SMP_FROST_PENETRATION table.

Limitations of Transitional Freeze State Estimates

During temperature data analysis, there were multiple cases when temperatures were around 0 ^{o}C over a period of several days, pointing to a possibility of a transitional freeze state. However, these temperature trends were not consistently observed from one depth to another or for different years. Therefore, without supporting data (ER, moisture, soil salinity) or in cases of inconclusive supporting data trends, it was not possible to make definite conclusions whether or not the soil was in a transitional state.

Analysis of the sites that had similar temperature trends and had supporting ER and moisture data revealed that, although temperature values may indicate possible transitional state, low moisture and high ER values during the same period may provide evidence that soil may be in a freeze or no-freeze state. The following example demonstrates subjectivity of transitional state assignment based on temperature data alone. The temperature trend shown in figure 19 indicates the possibility of a transitional state of soil during the months of January and February 2001 based on temperatures just below 0 ^{o}C over an extended period of time. However, high ER values during the same period indicate that the state of soil is likely to be frozen. No moisture data are available for the same analysis period.

As a result of this limitation, the majority of freeze state estimates developed in this analysis study fall in either frozen or unfrozen categories. No transitional states were assigned based on the analysis of the temperature data alone, as that approach was found to be too subjective in absence of other supporting information (moisture, ER, soil salinity). When supporting ER and moisture data were available, a more detailed trend analysis was conducted resulting in a limited number of transitional state assignments.

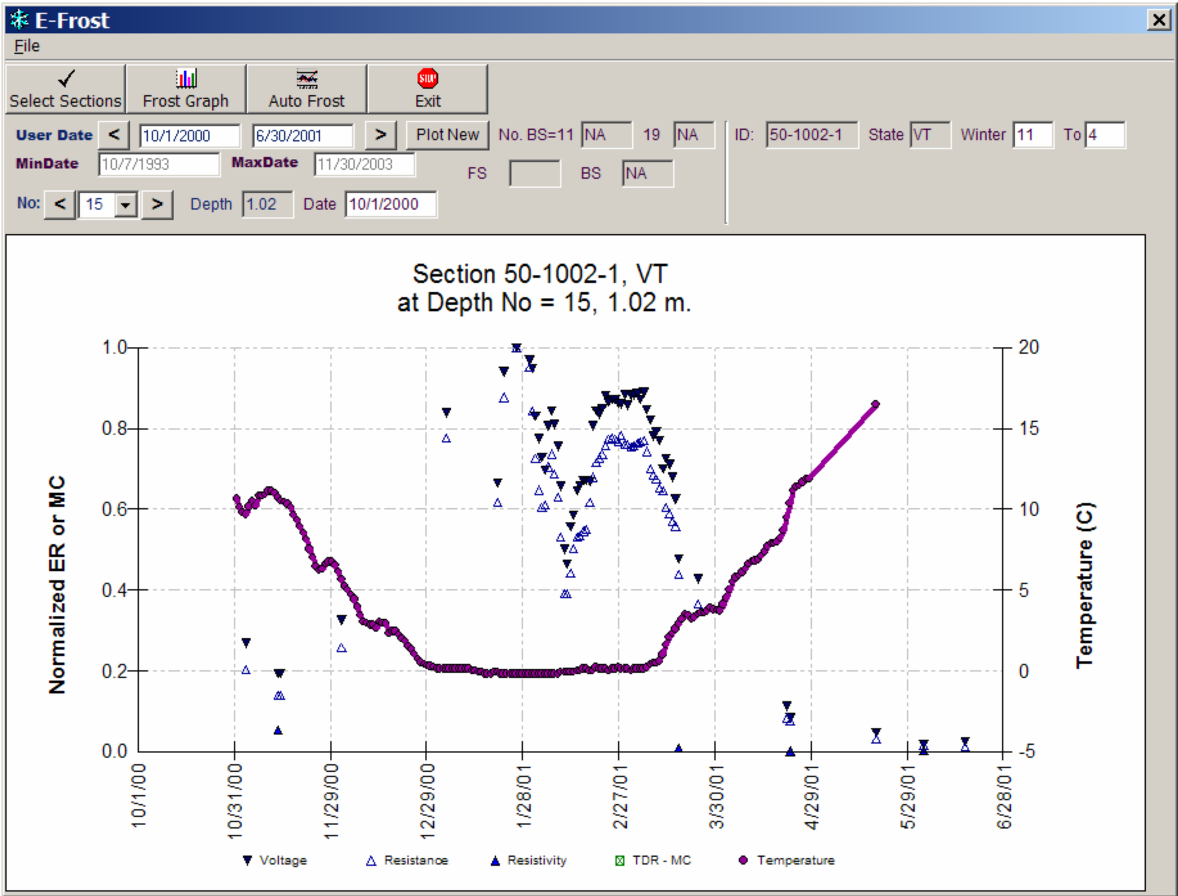


Figure 19. Chart. Temperature and ER trends at 1.02 m (3.35 ft) for site 50-1002 during winter season 2000–2001.

CHAPTER 6. LTPP DATA USED FOR FROST DETERMINATION

During Phase I of the project, the research team assessed the availability of the LTPP data needed to support the enhanced algorithm for evaluation of frost penetration. This assessment included data utilized by the existing FROST procedure and the LTPP data that will be utilized by the enhanced FROST procedure. The results of the assessment are summarized in this section.

DATA REQUIRED FOR E-FROST ANALYSIS

The following LTPP database tables containing subsurface temperature, electrical resistivity, and moisture data were used to determine frost penetration under bound pavement layers:

- SMP_ERESIST_AUTO_ABF—Contains new ER measurements (VOLTAGE and RESISTANCE) for SMP II sections.
- SMP_ERESIST_AUTO—Contains automated electrical contact voltage data for each electrode number.
- SMP_ERESIST_MAN_4POINT—Contains manually collected four point electrical contact resistance measurements:
    - Voltage reading between voltage electrodes.
    - Electrical current reading between current electrodes.
    - Computed electrical resistivity.
- SMP_ERESIST_MAN_CONTACT—Contains manually collected two point electrical contact resistance measurements:
    - Voltage reading between electrodes.
    - Electrical current reading between electrodes.
    - Computed contact resistance between two electrodes.
- SMP_ERESIST_DEPTHS—Contains depth from the pavement surface for each electrode.
- SMP_MRCTEMP_AUTO_DAY_STATS—Contains daily pavement subsurface temperature for the thermistors in the MRC thermistor probe closest to the surface.
- SMP_MRCTEMP_DEPTHS—Contains the installed thermistor depth.
- SMP_ERESIST_ABF_REF_VA—Contains background information related to ER measurements using ABF equipment for SMP II sections (this table is not be used directly in the ER data processing).
- SMP_TDR_AUTO_MOISTURE—Contains computed volumetric moisture content in percentile form.
- SMP_TDR_MANUAL_MOISTURE—Contains volumetric moisture content in percentile form based on most probable value of apparent length interpreted from manual TDR trace.

- SMP_TDR_DEPTHS_LENGTH TDR_DEPTH— Contains depth from pavement surface to TDR probe in meters.

Data from 1993 to 2001 were used to reinterpret previous frost estimates, and data from 2001 to 2004 were used to develop new frost estimates.

DATA REQUIRED FOR EICM ANALYSIS

In applying the EICM, the project team used section-specific data where they were available and pertinent to subsurface temperature prediction. The actual climatic measurements, layer, and material information collected at the site were used as inputs to the EICM. These measurements are included in the following tables:

- INV_ID—Contains longitude, latitude and elevation information.
- INV_GRADATION—Contains information about particle sizes.
- TST_L05B— Contains information about number of layers, layer and material type and layer thickness.
- TST_UG04_SS03—Contains information about plasticity index.
- TST_SS11—Contains hydraulic conductivity and initial water content information.
- TST_UG09—Contains hydraulic conductivity information.
- SMP_ATEMP_RAIN_DAY—Contains daily air temperature and rainfall statistics.
- SMP_ATEMP_RAIN_HOUR—Contains hourly ambient air temperature and rainfall.
- SMP_DRY_DENSITY—Contains subgrade dry density measurements.
- SMP_ELEV_AC_DATA—Contains AC surface elevation measurements.
- SMP_ELEV_PCC_DATA—Contains PCC surface elevation measurements.
- SMP_GRAV_MOIST—Contains pavement subsurface gravimetric moisture content.
- SMP_MRCTEMP_AUTO_DAY_STATS—Contains daily pavement subsurface temperature statistics.
- SMP_WATERTAB_DEPTH_MAN—Contains automated data on the depth to ground water table.
- CLM_VWS_TEMP_DAILY—Contains daily temperature data.
- CLM_VWS_WIND_DAILY—Contains daily wind data.
- AWS_DAILY_DATA—Contains daily temperature and wind data.

Default or assumed values were used for some of the required data elements that were not included in the LTPP database. The climatic data from the National Climatic Data Center for a specified longitude and latitude were used where section-specific weather data were not available. These climatic data are integrated in the EICM program. EICM inputs are provided in appendix B.

ANALYSIS DATABASE SUMMARY

The data from the LTPP tables discussed above were assembled in the analysis database. All records were organized by LTPP site, date, and measurement depth. For each analysis site and date, up to 35 records containing ER, temperature, and moisture data were prepared—one for each analysis depth.

One of the issues in processing electrical resistivity, moisture, and soil temperature data was that these data elements are measured at different depths. Therefore, data manipulation was required to correlate various electrical resistivity, soil temperature, and moisture values. To preserve the same interpretation depths as were used in the previous LTPP frost studies,[3] linear interpolation was used to obtain soil temperature and moisture values at the ER interpretation depth. In the previous LTPP frost studies, ER interpretation depth was defined as a middepth between two neighboring electrodes, resulting in 35 analysis depths for 36 electrodes included in the resistivity probe.

Only dates that had either ER or temperature data were included in the analysis database. Records for the months with the minimum monthly temperature above +1 ^{o}C and with no ER data were not included in the analysis database because no freeze conditions are possible when temperatures are above +1 ^{o}C.

EICM-predicted temperatures were added to the database to fill in the gaps in measured temperature data. EICM predictions were provided only for the sites that had sufficient site-specific EICM inputs. Only gaps of less than one month were filled with EICM predicted temperature values. Source of temperature data was specified in the analysis database to differentiate between measured and predicted temperature data.

Table 5 summarizes the number of records that were assembled in the analysis database for each of the 41 LTPP SMP sites included in the frost study. As can be seen, measured temperature data were the most complete data element, corresponding to the largest number of records in the analysis database.

Table 5. Summary of data assembled for frost penetration analysis.

State code	SHRP ID	Years with data	Days with data	Minimum date	Maximum date	Number of ER data records	Number of measured temperature records	Number of EICM-modeled temperature records	Number of volumetric moisture records
4 (AZ)	1024	4	22	9/14/1995	11/19/1998	770	490	0	561
8 (CO)	1053	5	285	7/1/1993	9/26/1997	1,320	9,286	0	587
9 (CT)	1803	5	277	8/19/1993	10/16/1997	1,375	9,102	0	1,042
16 (ID)	1010	5	355	10/1/1993	6/26/1997	1,235	10,596	1,157	1,031
18 (IN)	3002	4	250	9/8/1995	9/28/1998	412	8,273	0	280
20 (KS)	4054	4	117	8/25/1995	11/19/1998	694	3,671	0	477
23 (ME)	1026	5	466	9/16/1993	10/21/1997	1,324	15,801	0	888
24 (MD)	1634	4	142	5/12/1995	4/8/1998	978	4,445	0	823
25 (MA)	1002	2	83	9/1/1993	10/26/1994	490	2,625	0	227
27 (MN)	1018	7	568	8/24/1993	9/8/1997	1,569	19,022	0	628
27 (MN)	1028	5	835	9/9/1993	9/10/1997	1,352	28,844	0	691
27 (MN)	4040	5	629	9/22/1993	9/9/1997	1,420	20,448	1,088	767
27 (MN)	6251	10	1,486	9/15/1993	10/8/2003	2,110	50,401	774	1,128
30 (MT)	0114	5	896	7/16/2000	9/22/2004	7,876	30,038	0	26,000
30 (MT)	8129	6	326	8/12/1992	10/1/1997	1,728	10,194	0	498
31 (NE)	0114	7	441	8/8/1995	7/11/2002	1,203	13,382	0	637
31 (NE)	3018	9	724	8/11/1995	12/31/2003	1,446	22,852	1,922	825
32 (NV)	0101	6	355	11/6/1996	3/19/2003	4,267	10,399	0	4,889
32 (NV)	0204	2	67	12/1/1996	9/9/1997	239	2,234	0	196
33 (NH)	1001	5	417	10/14/1993	10/22/1997	1,219	14,078	0	652
34 (NJ)	0504	3	170	2/11/2002	3/13/2004	1,915	3,924	0	0
34 (NJ)	0505	3	186	2/11/2002	4/7/2004	2,695	3,925	0	0
34 (NJ)	0506	3	179	2/1/2002	4/7/2004	1,610	2,579	1,285	0
34 (NJ)	0507	3	174	2/2/2002	4/7/2004	1,295	3,913	0	0
34 (NJ)	0902	3	147	3/26/2002	4/7/2004	2,415	3,363	87	0
36 (NY)	0801	10	913	8/23/1995	3/31/2004	15,408	29,258	1,713	11,141
36 (NY)	4018	5	442	10/28/1993	10/14/1997	1,252	14,961	0	707
39 (OH)	0204	2	45	3/18/1998	10/14/1999	504	1,290	0	282
39 (OH)	0901	6	720	1/1/1998	10/16/2003	1,218	22,360	2,354	562
42 (PA)	1606	8	656	8/10/1995	10/15/2003	1,715	21,950	0	1,410
46 (SD)	0804	9	1,113	7/15/1994	12/16/2003	22,741	36,826	0	15,384
46 (SD)	9187	4	344	7/19/1994	9/23/1997	827	9,759	1,928	629
49 (UT)	1001	5	143	10/14/1993	9/24/1997	1,155	3,999	0	894
49 (UT)	3011	5	281	8/3/1993	9/22/1997	1,338	9,367	0	765
50 (VT)	1002	10	1,270	10/7/1993	11/30/2003	12,278	42,387	941	11,498
56 (WY)	1007	5	393	8/11/1993	9/30/1997	1,285	13,147	0	989
83 (MB)	1801	11	2,116	10/13/1993	11/10/2003	27,051	60,475	0	20,476
83 (MB)	3802	6	458	10/15/1993	11/5/1998	1,150	13,268	0	643
87 (ON)	1622	5	469	9/23/1993	10/30/1997	1,393	15,864	0	947
89 (QC)	3015	9	1,605	9/30/1993	6/6/2001	1,635	55,570	0	1,044
90 (SK)	6405	6	755	10/6/1993	5/31/1999	1,255	25,815	0	1,031
Total Records						**135,162**	**680,181**	**13,249**	**111,229**

CHAPTER 7. FROST PENETRATION ANALYSIS RESULTS

DATA ANALYSIS SUMMARY

Using the E-FROST research analysis tool, all previously processed sections with ER data were reprocessed using the enhanced analysis methodology presented in chapter 4, and new frost depths and layer estimates were determined. In addition to the reinterpretation of the previously processed data, all SMP II sections with ER data that had not been previously analyzed were analyzed using E-FROST, and new frost depths and layer estimates were prepared for the LTPP database upload. The analysis results, as well as the LTPP computed parameters developed under this project, were reviewed thoroughly.

Frost penetration analysis was conducted for 41 LTPP sites from the SMP I and II experiments. The schematic location of LTPP sites used in the frost penetration analysis study is shown in figure 21. Data from 21,953 dates were analyzed, and frost penetration depths were estimated. There were between 2 and 11 years of data analyzed for the different LTPP sites. Detailed frost penetration results were reported in two LTPP computed parameters tables discussed later in this chapter.

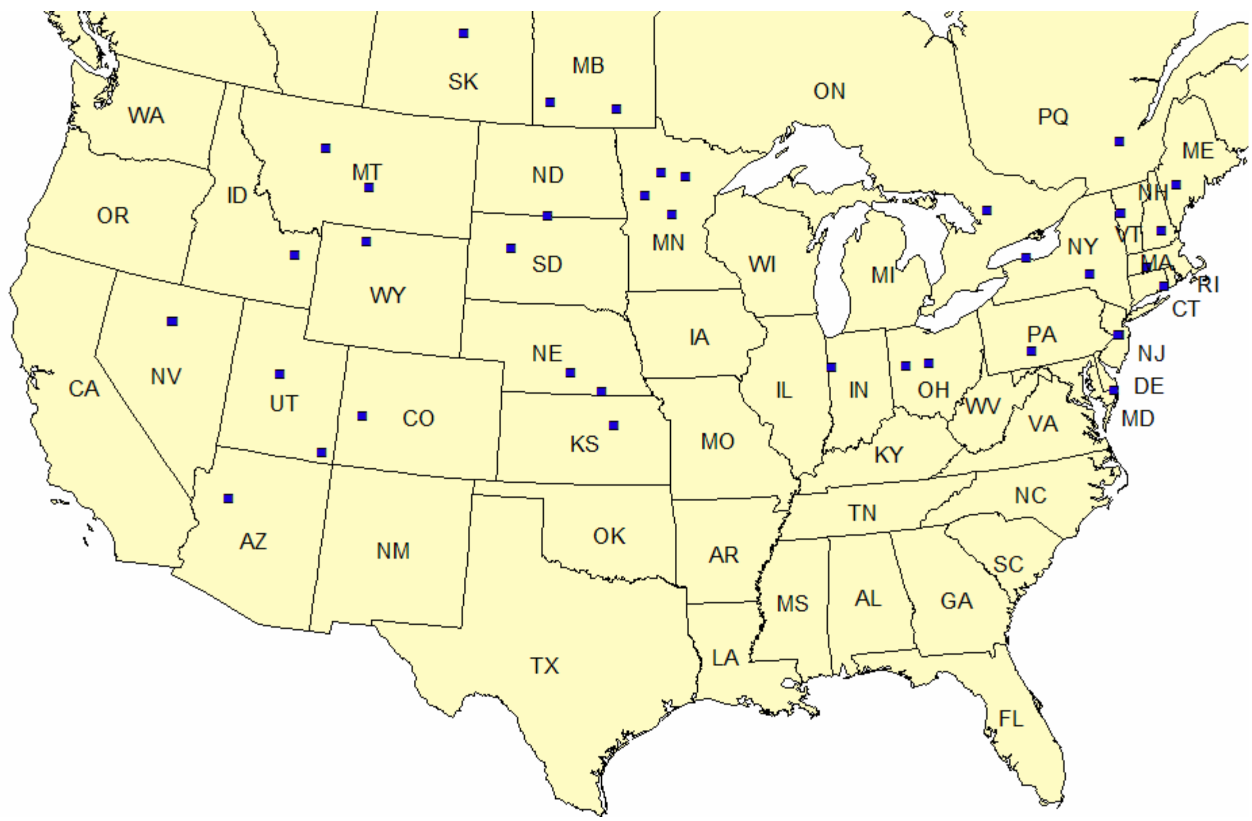


Figure 20. Picture. Locations of LTPP SMP sites analyzed in this study.

FROST OBSERVATIONS

Observations discovered during the project are described in this section.

Severity of Frost Penetration

Using the results of the frost penetration analysis, average and maximum frost depths were determined, along with the first and the last cold month with freeze conditions for each LTPP site with in-situ measurement data. This information could be used to assess the severity of frost penetration at different LTPP sites.

Maximum freeze depth corresponds to the maximum frost depth for the year with the deepest frost penetration detected during the analysis. Maximum frost depth is used in the design to account for the worst case scenario.

Average maximum freeze depth corresponds to the average of maximum frost depths based on all years used in the analysis and represents average or typical frost penetration conditions.

The first and the last months with freeze conditions are based on the worst case scenario. These months were determined by reviewing frost data for all available years and selecting the earliest month at the beginning of the freeze period and the latest months at the end of the freeze period. A summary of frost determinations is provided in table 6.

Frost penetration profiles generated for all Minnesota, Manitoba, and Saskatchewan sites and site 4018 in New York indicate that frost penetration goes beyond the last interpretation depth. For Arizona site 1024 and Nevada site 0101, the first interpretation depth was lower than the expected frost penetration depth. These cases are noted by starred comments in table 6.

Table 6. Summary of frost determinations.

STATE CODE	SHRP ID	Number of years analyzed	Average max freeze depth, m	Maximum freeze depth, m	First freeze month	Last freeze month
4 (AZ)	1024	4	*	*	--	--
8 (CO)	1053	5	0.336	0.374	DEC	FEB
9 (CT)	1803	5	0.544	0.794	JAN	MAR
16 (ID)	1010	5	0.763	0.864	NOV	FEB
18 (IN)	3002	4	1.036	1.213	DEC	FEB
20 (KS)	4054	4	1.056	1.056	JAN	FEB
23 (ME)	1026	5	1.107	1.819	NOV	APR
24 (MD)	1634	4	0.436	0.436	FEB	FEB
25 (MA)	1002	2	1.017	1.017	JAN	MAR
27 (MN)	1018	5	1.791	2.181***	NOV	APR
27 (MN)	1028	5	2.275	2.386***	NOV	APR
27 (MN)	4040	5	1.900	2.317***	NOV	MAY
27 (MN)	6251	10	2.126	2.308***	NOV	APR
30 (MT)	0114	5	1.165	1.256	NOV	MAR
30 (MT)	8129	6	0.793	1.082	NOV	MAR
31 (NE)	0114	7	0.844	1.173	DEC	MAR
31 (NE)	3018	9	1.289	1.679	DEC	MAR
32 (NV)	0101	6	**	**	—	—
32 (NV)	0204	2	0.612	0.612	DEC	JAN
33 (NH)	1001	5	0.954	1.394	DEC	MAR
34 (NJ)	0504	3	0.406	0.406	JAN	FEB
34 (NJ)	0505	3	0.458	0.458	JAN	FEB
34 (NJ)	0506	3	0.608	0.608	JAN	FEB
34 (NJ)	0507	3	0.455	0.455	JAN	JAN
34 (NJ)	0902	3	0.643	0.668	JAN	FEB
36 (NY)	0801	10	0.627	0.988	DEC	MAR
36 (NY)	4018	5	1.090	2.102***	DEC	APR
39 (OH)	0204	2	0.705	0.705	JAN	JAN
39 (OH)	0901	6	0.704	0.776	DEC	FEB
42 (PA)	1606	8	0.568	0.771	DEC	MAR
46 (SD)	0804	9	1.445	1.998	NOV	APR
46 (SD)	9187	4	1.243	1.827	NOV	APR
49 (UT)	1001	5	1.557	2.019	DEC	DEC
49 (UT)	3011	5	0.553	0.692	DEC	FEB
50 (VT)	1002	10	1.020	1.498	NOV	APR
56 (WY)	1007	5	0.741	0.999	NOV	MAR
83 (MB)	1801	11	2.033	2.13***	OCT	MAY
83 (MB)	3802	6	1.798	2.424***	NOV	MAY
87 (ON)	1622	5	1.194	1.743	NOV	APR
89 (QC)	3015	9	1.316	1.587	NOV	MAY
90 (SK)	6405	6	1.999	2.058***	OCT	MAY

1 m = 3.28 ft
— No data available.
* First interpreted depth at 0.38 m.
** First interpreted depth at 0.51 m.
*** Possibility of frost beyond the last interpreted depth.

Frost Penetration Profile Characteristics

Using frost estimates computed based on in-situ data, frost penetration profiles were analyzed for each of the 41 LTPP sites for all available years of data. The changes in frost profiles over the cold seasons (fall, winter, and spring) were examined for each available year. The review indicated that even for similar frost depths, the observed profiles varied from site to site and year to year. Hence, knowledge of the maximum frost depth without an understanding of seasonal changes in frost penetration profile would not be enough for accurate characterization of seasonal changes in pavement structural characteristics.

Some of the commonly observed frost penetration profile characteristics were multiple freeze thaw cycles, shallow fall freeze with thaw followed by solid deep freeze with a spring thaw, and solid freeze with spring thaw and refreeze. Figure 21 through figure 23 show examples of each of these commonly observed frost penetration profiles.

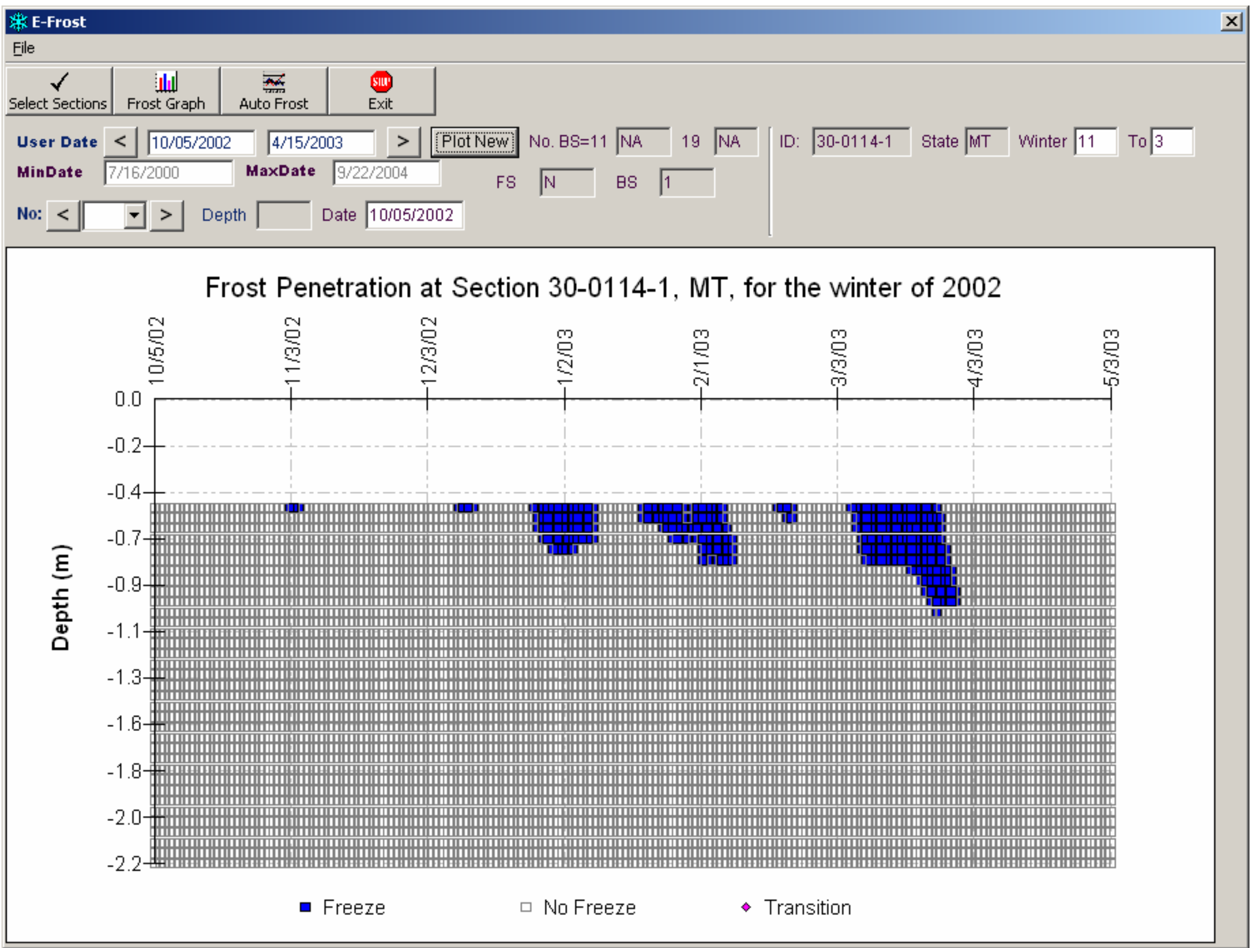


Figure 21. Chart. Frost penetration profile showing multiple freeze-thaw cycles.

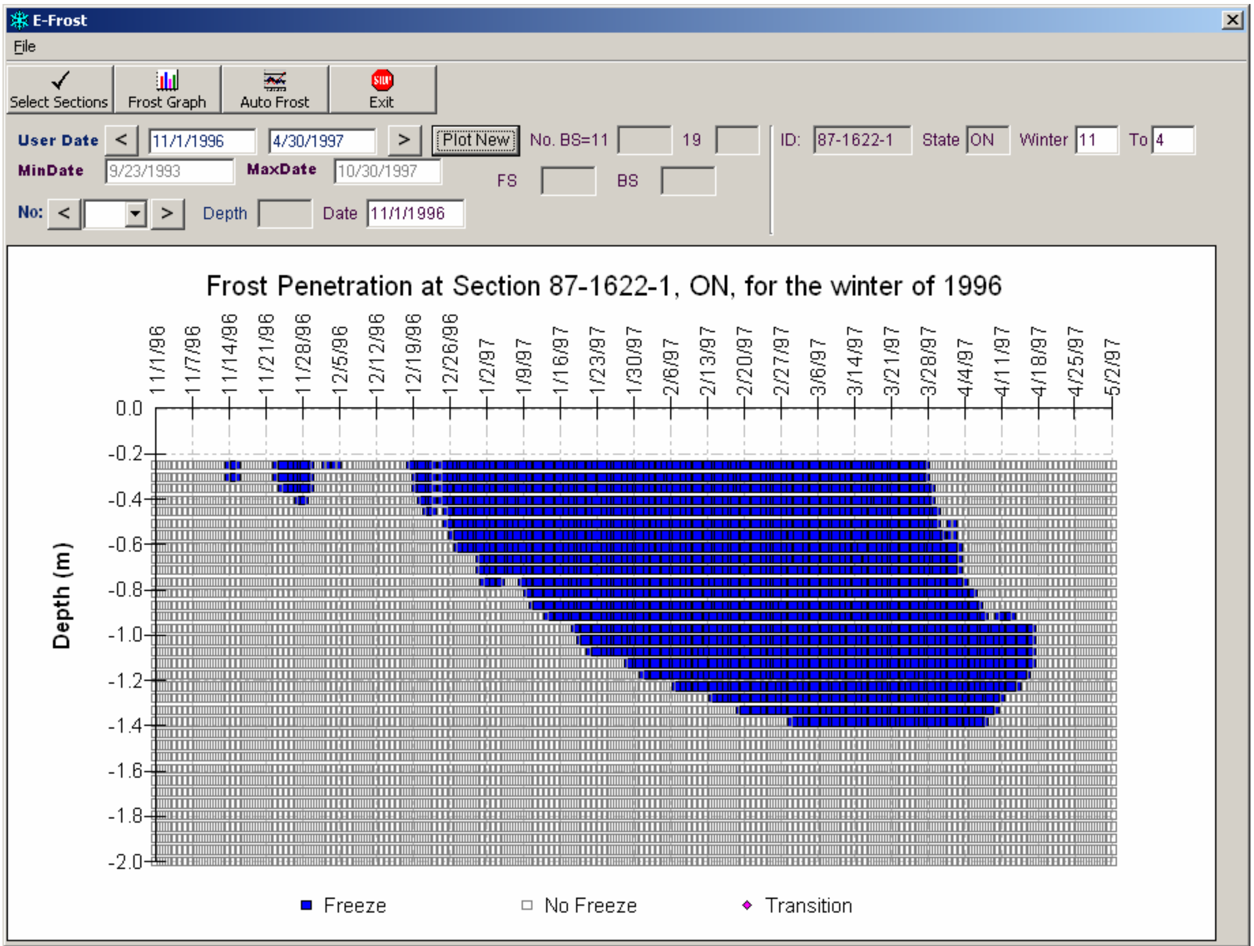


Figure 22. Chart. Frost penetration profile showing shallow freeze cycles in the fall followed by solid deep freeze with spring thaw.

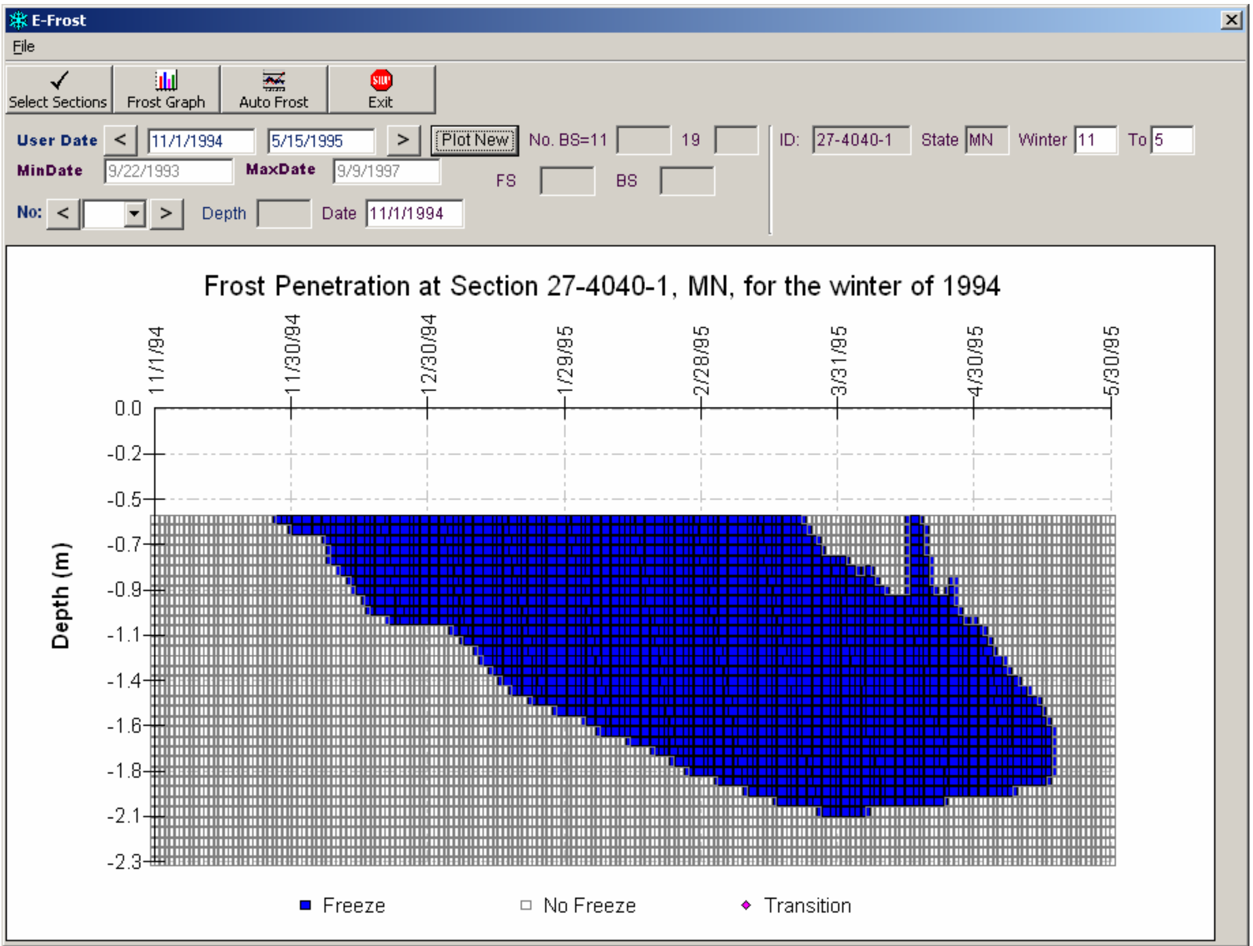


Figure 23. Chart. Frost penetration profile showing solid freeze with partial spring thaw and refreeze.

Table 7 summarizes typical frost penetration characteristics observed for each SMP site. To describe frost penetration profile characteristics, frost depth was characterized as shallow, medium, or deep. A shallow frost depth was defined between 0 and 0.6 m (0 and 1.97 ft); a medium frost depth was defined between 0.6 and 0.9 m (1.97 and 2.95 ft); and a deep frost depth was defined for frost that penetrated 0.9 m (2.95 ft) or more. Since these definitions are subjective, the seasonal maximum frost depth is also reported in the table for each site. Furthermore, the depth of the top of the first unbound layer was different for each SMP site, which occasionally limited frost determination at shallow and medium depths where the first unbound layer was placed below the expected freeze depth. The information in table 7 could be used to infer the typical frost penetration characteristics for LTPP SMP sites.

Table 7. Typical frost penetration profile characteristics for LTPP SMP sites.

State or province	State code	SHRP ID	#of years w/ data	Frost profile description		
				Fall (Sept 21–Dec 21)	Winter (Dec 22–Mar 20)	Spring (Mar 21–June 21)
Arizona	4	1024	3	No Freeze*	No Freeze*	No Freeze*
Colorado	8	1053	3	No Freeze	Multiple Shallow Freeze-Thaw Cycles (up to 0.37 m)	No Freeze
Connecticut	9	1803	4	No Freeze	Shallow or Medium freeze-thaw (up to 0.79 m)	No Freeze
Idaho	16	1010	3	Possible Medium Freeze-Thaw Re-freeze (up to 0.66 m)	Multiple Shallow or Medium Freeze-Thaw Cycles (up to 0.86 m)	No Freeze
Indiana	18	3002	2	Medium Freeze-Thaw	Multiple Medium to Deep Freeze-Thaw Cycles (up to 1.21 m)	No Freeze
Kansas	20	4054	3	No Freeze	Multiple Medium to Deep Freeze-Thaw Cycles (up to 1.06 m)	No Freeze
Maine	23	1026	4	Shallow freeze-thaw re-freeze (up to 0.55 m)	Continuous Deep Freeze (up to 1.82 m)	Prolonged Deep Thaw (up to 1.77 m)
Manitoba	83	1801	9	Deep Freeze, possibly preceded by Shallow Freeze w/ Thaw (up to 1.72 m)	Continuous Deep Freeze (up to 2.13 m)***	Deep Freeze, Shallow Thaw followed by Re-freeze, Prolonged Deep Thaw (up to 2.13 m)***
Manitoba	83	3802	4	Deep Freeze (up to 1.31m)	Continuous Deep Freeze (up to 2.42 m)***	Deep Freeze, Shallow Thaw followed by Re-freeze, Prolonged Deep Thaw (up to 2.42 m)***
Maryland	24	1634	4	No Freeze	Shallow freeze-thaw (up to 0.44 m)	No Freeze
Massachusetts	25	1002	2	No Freeze	Deep Freeze w/ Thaw, followed by Medium Freeze w/ Thaw (up to 1.02 m)	No Freeze
Minnesota	27	1018	4	Medium to Deep Freeze (up to 1.83 m)	Deep Freeze, Shallow Thaw followed by Re-freeze (up to 2.18 m)	Prolonged Deep Thaw (up to 2.13 m)
Minnesota	27	1028	3	Deep Freeze, possibly proceeded by Medium Freeze w/ Thaw. (up to 1.83 m)	Continuous Deep Freeze (up to 2.39 m)***	Deep Freeze, Possible Shallow Thaw followed by Re-freeze, Prolonged Deep Thaw (up to 2.39 m)***
Minnesota	27	4040	3	Deep Freeze (up to 1.20 m)	Deep Freeze, Possible Shallow Thaw followed by Re-freeze (up to 2.32 m)***	Prolonged Deep Thaw (up to 2.3 2m)***

Table 7. Typical frost penetration profile characteristics for LTPP SMP sites—continued.

State or province	State code	SHRP ID	#of years w/ data	Frost profile description		
				Fall (Sept 21–Dec 21)	Winter (Dec 22–Mar 20)	Spring (Mar 21–June 21)
Minnesota	27	6251	8	Deep Freeze (up to 1.85 m)	Deep Freeze, Possible Shallow Thaw followed by Re-freeze (up to 2.31 m)***	Prolonged Deep Thaw (up to 2.31 m)***
Montana	30	0114	4	Multiple Shallow/Medium Freeze-Thaw Cycles or Deep Freeze (up to 1.05 m)	Multiple Medium/Deep Freeze-Thaw Cycles or Deep Freeze with Shallow Thaw and Re-freeze (up to 1.26 m)	Possible Deep Freeze and Thaw (up to 0.95 m)
Montana	30	8129	3	Medium Freeze (up to 0.83 m)	Multiple Medium/Deep Freeze-Thaw Cycles (up to 1.08 m)	No Freeze
Nebraska	31	0114	6	Medium Freeze w/ Thaw (up to 0.67 m)	Multiple Medium/Deep Freeze-Thaw Cycles (up to 1.17 m)	No Freeze
Nebraska	31	3018	8	Possible Deep Freeze (up to 1.2 2m)	Deep Freeze (up to 1.68 m)	No Freeze
Nevada	32	0101	5	No Freeze**	No Freeze**	No Freeze**
Nevada	32	0204	1	No Freeze	Multiple Shallow Freeze-Thaw Cycles (up to 0.61 m)	No Freeze
New Hampshire	33	1001	4	Possible Shallow Freeze w/ Thaw (up to 0.33 m)	Multiple Medium/Deep Freeze-Thaw Cycles or Single Deep Freeze (up to 1.39 m)	Possible Thaw (up to 1.19 m)
New Jersey	34	0504	3	No Freeze	Multiple Shallow Freeze-Thaw Cycles (up to 0.41 m)	No Freeze
New Jersey	34	0505	3	No Freeze	Multiple Shallow Freeze-Thaw Cycles (up to 0.46 m)	No Freeze
New Jersey	34	0506	2	No Freeze	Medium Freeze-Thaw (up to 0.61m)	No Freeze
New Jersey	34	0507	3	No Freeze	Shallow Freeze-Thaw (up to 0.46 m)	No Freeze
New Jersey	34	0902	3	No Freeze	Multiple Shallow/Medium Freeze-Thaw Cycles (up to 0.67 m)	No Freeze
New York	36	0801	7	Multiple Shallow Freeze-Thaw Cycles (up to 0.48 m)	Multiple Shallow to Deep Freeze-Thaw Cycles or Single Deep Freeze (up to 0.99 m)	Possible Multiple Shallow Freeze-Thaw Cycles (up to 0.28 m)
New York	36	4018	4	No Freeze	Multiple Shallow to Deep Freeze-Thaw Cycles or Single Deep Freeze (up to 2.10 m)***	Possible Shallow Freeze-thaw or Prolonged Deep Thaw (up to 2.10 m)***

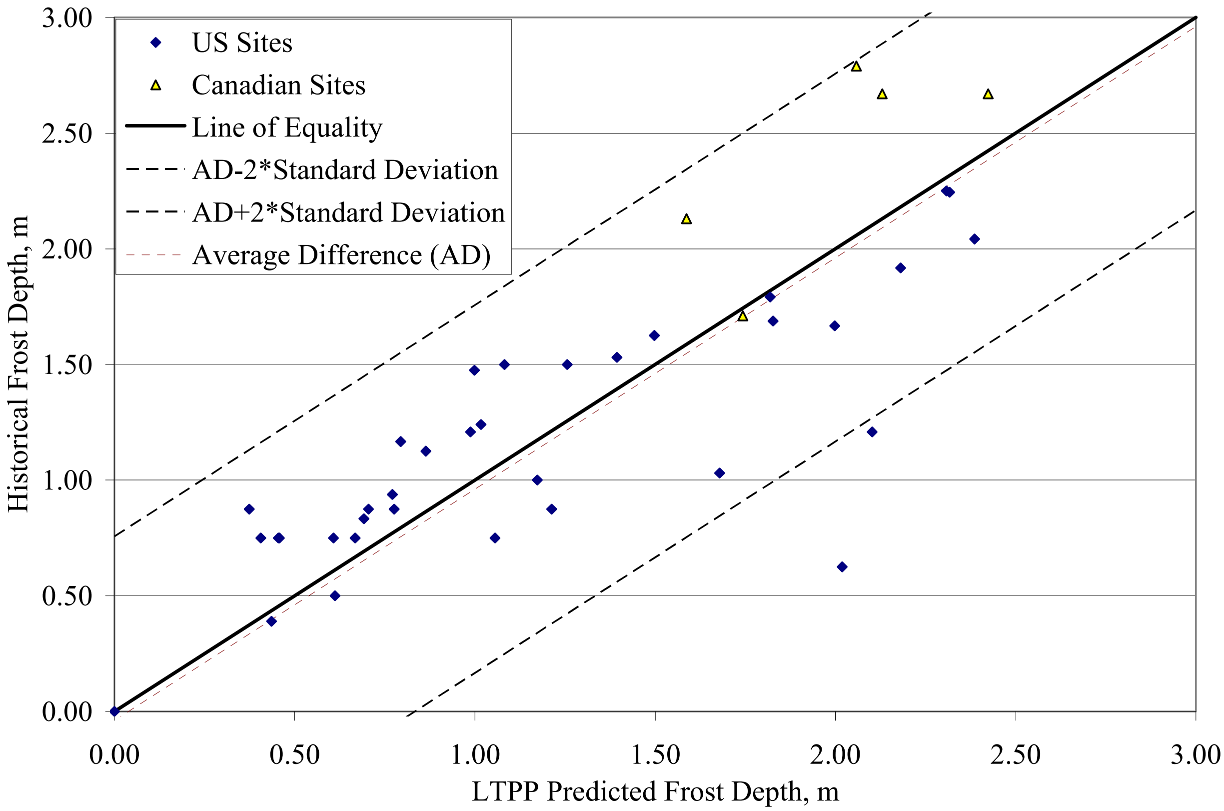
Table 7. Typical frost penetration profile characteristics for LTPP SMP sites—continued.

State or province	State code	SHRP ID	#of years w/ data	Frost profile description		
				Fall (Sept 21–Dec 21)	Winter (Dec 22–Mar 20)	Spring (Mar 21–June 21)
Ohio	39	0204	2	No Freeze	Medium Freeze-Thaw (up to 0.71 m)	No Freeze
Ohio	39	0901	6	Possible Medium Freeze (up to 0.57 m)	Multiple (B) Shallow to Medium Freeze-Thaw Cycles (up to 0.78 m)	No Freeze
Ontario	87	1622	4	Multiple Shallow Freeze-Thaw Cycles (up to 0.42 m)	Single Deep Freeze or Multiple Deep Freeze-Thaw Cycles (up to 1.74 m)	Possible Shallow Freeze-Thaw, Prolonged Deep Thaw (up to 1.69 m)
Pennsylvania	42	1606	8	Multiple Shallow Freeze-Thaw Cycles (up to 0.42 m)	Multiple Shallow to Medium Freeze-Thaw Cycles (up to 0.77 m)	No Freeze
Quebec	89	3015	6	Shallow to Medium Freeze-Thaw followed by Deep Freeze (up to 1.03 m)	Deep Freeze, Shallow Thaw followed by Re-freeze (up to 1.54 m)	Prolonged Deep Thaw, Possible Deep Freeze (up to 1.59 m)
Saskatchewan	90	6405	3	Shallow Freeze-Thaw, followed by Deep Freeze (up to 1.80 m)	Continuous Deep Freeze (up to 2.06m)***	Deep Freeze, Multiple Shallow Thaw & deep Re-freeze periods, Prolonged Deep Thaw (up to 2.06 m)***
South Dakota	46	0804	7	Medium Freeze-Thaw, followed by Medium to Deep Freeze (up to 1.24 m)	Deep Freeze, Possible Shallow Thaw followed by Re-freeze (up to 2.00 m)	Deep Freeze, Possible Shallow Thaw followed by Re-freeze, Prolonged Deep Thaw (up to 1.95 m)
South Dakota	46	9187	2	Multiple shallow Freeze-Thaw Cycles followed by Medium to Deep Freeze (up to 1.02 m)	Deep Freeze, Multiple Shallow Thaw followed by Re-freeze Cycles up to 1.83 m)	Medium to Deep Freeze, Shallow Thaw & Re-freeze periods, Prolonged Thaw (up to 1.63 m)
Utah	49	1001	3	Mid Depth to Deep Freeze (up to 2.02 m)	No Freeze	No Freeze
Utah	49	3011	3	No Freeze Period	Multiple Shallow to Medium Freeze-Thaw Cycles (up to 0.69 m)	No Freeze
Vermont	50	1002	8	Multiple Shallow to Medium Freeze-Thaw Cycles (up to 0.64 m)	Multiple Shallow to Deep freeze-thaw cycles, Possible Continuous Deep Freeze (up to 1.50 m)	Possible Deep Thaw (up to 1.40 m)
Wyoming	56	1007	3	Multiple Shallow Freeze-Thaw Cycles (up to 0.49 m)	Multiple Shallow to Deep Freeze-Thaw Cycles (up to 1.00 m)	No Freeze

1 m = 3.28 ft
* First interpreted depth at 0.38 m.
** First interpreted depth at 0.51 m.
*** Possibility of frost beyond the last interpreted depth.

Comparison with Historical Non-LTPP Frost Data

The computed maximum frost penetration depths were compared to the historical frost penetration values, as published in the climatic maps developed by NOAA[(1)] and Environment Canada.[(2)] Data from the historical maps were interpolated to the LTPP site locations. The results of the comparison are shown in figure 24.



1 m = 3.28 ft

Figure 24. Graph. Comparison of frost penetration depths.

The graph in figure 24 shows a good overall agreement between LTPP and historical maximum frost depth predictions. Some of the differences can be attributed to the fact that, while comparisons are provided for the same region, the historical values are not site-specific and that local variations are possible due to factors such as soil type, moisture content, altitude, and land development. In addition, for Canadian sites, some inaccuracies could result from estimation of frost depth from the freezing index data provided on the climatic map. For the three Canadian sites shown in the upper-right corner on the graph, LTPP frost penetration profiles indicate the possibility of frost beyond the last interpreted depth; however, the full frost depth cannot be established as no LTPP measurements are available at these lower depths.

The extreme frost predictions for U.S. sites provided on the NOAA map are based on longer monitoring period than the LTPP frost predictions; hence, covering more seasons where extreme conditions could occur. Table 8 contains data used in the analysis.

Table 8. Comparison of average frost depth for LTPP SMP sites.

STATE_CODE	SHRP_ID	Number of years analyzed	LTPP maximum freeze depth, m	Historic maximum freeze depth, m
4 (AZ)	1024	4	*	0.250
8 (CO)	1053	5	0.374	0.875
9 (CT)	1803	5	0.794	1.167
16 (ID)	1010	5	0.864	1.125
18 (IN)	3002	4	1.213	0.875
20 (KS)	4054	4	1.056	0.750
23 (ME)	1026	5	1.819	1.792
24 (MD)	1634	4	0.436	0.390
25 (MA)	1002	2	1.017	1.240
27 (MN)	1018	5	2.181***	1.917
27 (MN)	1028	5	2.386***	2.042
27 (MN)	4040	5	2.317***	2.245
27 (MN)	6251	10	2.308***	2.250
30 (MT)	0114	5	1.256	1.500
30 (MT)	8129	6	1.082	1.500
31 (NE)	0114	7	1.173	1.000
31 (NE)	3018	9	1.679	1.031
32 (NV)	0101	6	**	0.600
32 (NV)	0204	2	0.612	0.500
33 (NH)	1001	5	1.394	1.531
34 (NJ)	0504	3	0.406	0.750
34 (NJ)	0505	3	0.458	0.750
34 (NJ)	0506	3	0.608	0.750
34 (NJ)	0507	3	0.455	0.750
34 (NJ)	0902	3	0.668	0.750
36 (NY)	0801	10	0.988	1.208
36 (NY)	4018	5	2.102***	1.208
39 (OH)	0204	2	0.705	0.875
39 (OH)	0901	6	0.776	0.875
42 (PA)	1606	8	0.771	0.938
46 (SD)	0804	9	1.998	1.667
46 (SD)	9187	4	1.827	1.688
49 (UT)	1001	5	2.019	0.625
49 (UT)	3011	5	0.692	0.833
50 (VT)	1002	10	1.498	1.625
56 (WY)	1007	5	0.999	1.475
83 (MB)	1801	11	2.13***	2.670
83 (MB)	3802	6	2.424***	2.670
87 (ON)	1622	5	1.743	1.710
89 (QC)	3015	9	1.587	2.130
90 (SK)	6405	6	2.058***	2.790

1 m = 3.28 ft

* First interpreted depth at 0.38 m.

** First interpreted depth at 0.51 m.

*** Possibility of frost beyond the last interpreted depth.

Comparison with Previous LTPP Frost Estimates

When comparing the results of the current frost penetration data analysis to the previous results, the following improvements can be noted:

- The new methodology resulted in the development of the complete frost penetration time histories for LTPP SMP I and II sites, instead of previously reported freeze depth snapshots based on ER measurement dates. Frost penetration information for the previously analyzed periods increased over 8 times by the addition of results for the 14,903 dates that previously were not included in the analyses.
- Analysis of frost penetration histories led to the discovery of multiple freeze-thaw periods or of freeze-thaw periods during late fall or early spring characteristic for several LTPP sites, as discussed in this chapter. This information previously was not available. This new information is important for understanding and tracking of seasonal changes in pavement structural responses.
- Analysis based on cross-referenced ER, moisture, and temperature data provided means far more informed and less subjective determinations of frost penetration for the LTPP sites compared to the previous estimates. ER and moisture data used in freeze state analysis are provided in the LTPP SMP_FREEZE_STATE table. Additionally, moisture data used in the analysis can be found in the LTPP SMP_TDR_MOISTURE table.
- Major differences with the previous LTPP frost information are the availability of frost predictions for longer freeze seasons, the availability of data on fall and spring partial thaw and refreeze and multiple freeze-thaw cycles for some sites, and deeper frost estimates for some sites.

LTPP FROST DATA TABLE DESCRIPTIONS

As a result of this data analysis effort, two tables were created for inclusion in the LTPP database. The proposed computed parameter tables (CPT) are based on the existing LTPP frost CPT tables with changes and additions made as a result of the current frost penetration analysis study.

These tables have the same names as in the previous LTPP database releases and are defined as follows:

- **SMP_FREEZE_STATE—**Contains the interpreted soil freeze state (F-frozen, N-no-frozen, and T-transitional or partially frozen) based on the soil temperature and electrical resistivity data and supplemented by the soil moisture data trend analysis. Caution: Only a limited number of transitional states were determined based on the methodology used in LTPP Frost study.
- **SMP_FROST_PENETRATION**—Contains the interpreted frozen layers and frost depth information, based on the interpreted freeze states (F-frozen and T-transitional or partially frozen) in table SMP_FREEZE_STATE. Caution: No frozen depths or layers were reported for depths and dates without sensor measurements. Use the SMP_FREEZE_STATE table to identify dates and depths that have no data.

These new tables contain freeze state interpretations for all the available temperature and ER data collected during the SMP I and II experiments. As such, the intent of these tables is to replace the existing SMP_FREEZE_STATE and SMP_FROST_PENETRATION tables.

Summaries of the information included in the CPT frost tables are provided in table 9 and table 10.

Table 9. Summary of information included in the revised table SMP_FREEZE_STATE.

Data element or parameter	DESCRIPTION
STATE code	State code
SHRP ID	SHRP identification code
SMP date	Date corresponding to SMP data collection
Interpretation depth number	Depth number where freeze state is interpreted, increasing from top downward.
Interpretation depth	Middepth between electrodes used in the freeze state interpretation, measured for pavement surface; two consecutive electrodes are used in voltage and contact resistance measurements and four in resistivity.
Interpreted freeze state	Interpreted freeze state at the interpret depth: F-Freeze, N-No-freeze, T-Transitional (or partial freeze).
Interpretation basis	Code indicating the basis for freeze state interpretation: 1. Freeze state based on temperature data using 0 ^{o}C freezing isotherm, not forced. 2. Freeze state determined by the analyst after reviewing the temperature, electrical resistivity, and moisture data trends. 3. Temperature data is not available. Freeze state determined by the analyst from ER and moisture.
Normalized resistivity	Electrical resistivity of the soil at the measurement depth, relative to the extreme values measured at that depth.
Normalized resistance	Electrical resistance of the soil at the measurement depth, relative to the extreme values measured at that depth.
Normalized voltage	Voltage drop of the soil at the measurement depth, relative to the extreme values measured at that depth.
Soil temperature	Average soil temperature of the day, calculated at the interpretation depth. This could either be based on interpolation of measured values, or derived using EICM.
Temperature source	Source of the temperature data used in freeze state interpretation: (1) based on measured, (2) derived using EICM.

Table 10. Summary of information included in the revised table SMP_FROST_PENETRATION.

Filed name	DESCRIPTION
STATE code	State code
SHRP ID	SHRP identification code
SMP date	Date corresponding to SMP data collection
Frozen layer	Code for interpreted frozen layer number. A value of zero indicates no frozen layers.
Top depth number	Serial number for the starting depth (top) of a frozen layer, increasing from pavement surface downward.
Bottom depth number	Serial number for the ending depth (bottom) of a frozen layer, increasing from pavement surface downward.
Freeze from	Starting (top) depth (meter) of a frozen layer, measured from the pavement surface.
Freeze to	Ending (bottom) depth (meter) of a frozen layer, measured from the pavement surface.

CHAPTER 8. SUMMARY AND RECOMMENDATIONS

SUMMARY

A comprehensive review of the previous LTPP frost penetration analysis methodology and an assessment of frost depth estimates provided in the LTPP database were conducted, followed by recommendations for improvements. As a result of these recommendations, an enhanced methodology and the accompanying E-FROST research analysis tool were developed for determination of frost penetration in unbound pavement layers and subgrade soil for LTPP SMP sections.

The enhanced methodology uses electrical resistivity, moisture, and soil temperature data collected for instrumented SMP sections to predict frost depth in unbound pavement layers. In addition, the EICM model was used to fill in the gaps in the measured soil temperature data.

Using the enhanced analysis methodology and E-FROST, in-situ data were analyzed to determine freeze conditions and frost depths in the unbound pavement layers. The results of the frost penetration analysis for LTPP SMP sections were assembled in the LTPP computed parameter tables described in this report.

The results presented in this report demonstrate how frost penetration beneath the pavement structure was predicted for LTPP SMP sites using a combined empirical and mechanistic technique. This technique utilizes data from LTPP in-situ measurements and thermodynamic modeling.

Study findings stress the importance of using all three different types of in-situ measurements for accurate frost penetrations prediction: temperature, electrical resistivity, and moisture content. The EICM has proven useful for filling in the gaps of measured subsurface temperatures and for understanding the thermodynamic processes that occur in pavement layers. This information could help practitioners and researchers design seasonal monitoring field experiments and analyze field data to determine frost penetration under pavement layers.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future E-FROST Development to Support M-E PDG Implementation

The E-FROST research tool developed during this study could be very useful for analysis of seasonal changes in unbound pavement layers. In the future, this tool could become particularly useful for implementation of the M-E PDG, which emphasizes estimating seasonal changes in pavement layer moduli.

We recommend that LTPP consider further development of this tool into an LTPP software product similar to the LTPP profile viewer software so that the pavement research and practicing community at large can have easy access to ER, temperature, and moisture data, as well as frost penetration profiles for LTPP SMP sites. In addition, data from FWD tests can be added to this software to relate changes in mechanistic properties of pavement layers and in pavement responses and to cross reference this information with frost penetration data.

Future LTPP Data Analysis Study of Pavement Responses under FWD Loading during Freeze-Thaw Conditions

During spring thaw, sunshine and warm air temperatures result in a top-down thawing of the pavement system. The water released by the melting ice can be trapped by deeper, still-frozen material, creating saturated or supersaturated conditions that weaken the pavement structure. The change in pavement strength could be observed by FWD measurements.

The database tables developed under this study provide detailed information about the periods and the depth of freeze-thaw based on continuous temperature, ER, and moisture data analyzed. This information could be utilized to cross reference with and analyze FWD data collected during the thaw periods to capture the conditions of the supporting layers during the weakest period and to correlate these conditions with pavement responses. This task can be accomplished through mechanistic modeling of pavement responses under FWD loading based on the inventory, climatic, testing, and FWD data from the LTPP database.

The result of the proposed study could contribute to understanding pavement deterioration, as triggered by seasonal changes in pavement layer moduli and could be utilized in the development of spring load restrictions.

Future Development of In-Situ Frost Measurement Devices

One of the challenges in LTPP frost penetration analysis was the interpretation of the data from ER measurement devices, as the following describes:

- ER measurements were expected to be high during cold winter months when temperatures plunge below ground water freezing point. However, a number of ER readings during warm summer months (with temperatures high above 0 ^{o}C) were found to be as high as readings during cold winter months. These were unexpected trends.

- LTPP collected in-situ data to evaluate three types of ER parameters: voltage, resistance, and resistivity. All three parameters are expected to follow a similar trend when soil goes through freeze and thaw cycles. However, it was not uncommon that the data showed opposite trends, or one of the trends would be nearly flat (indicating no changes in the soil freeze state). This inconsistency was unexpected.

We highly recommend that LTPP promote the need for future research and development of in-situ frost measurement devices. Perhaps the next generation of such devices would have multi-functional sensors capable of monitoring temperature and moisture changes in the soil, in addition to electrical resistivity measurements, and use output of all three types of measurements to determining frost penetration.

APPENDIX A. E-FROST USER'S GUIDE

INTRODUCTION

This guide is designed to familiarize new users with the E-FROST user interface and analysis options. The guide includes screen captures to help the user navigate through the software screens.

E-FROST was designed to view time-series data from the in-situ measurements (ER, temperature, and moisture) used in frost penetration analysis, to generate and view frost penetration profiles, and create frost penetration table documenting frost penetration depths for different dates for which in-situ measurements were taken.

E-FROST INSTALLATION AND REMOVAL

Complete the following steps to install E-FROST:

1. Make sure that all other applications are closed and that the E-FROST installation CD-ROM has been inserted into the CD-ROM drive.
2. From the Windows Start menu, select Run.
3. In the Run dialog box, type "(CD drive):setup.exe," where (CD drive) is the letter assigned to your CD-ROM drive.
4. Follow the simple instructions in the installation program. When installation is completed, E-FROST program will be available from the Start menu.

Complete the following steps to remove E-FROST:

1. Click the Start button and choose the Settings option.
2. Select Control Panel.
3. From the Control Panel, double-click the Add/Remove Programs icon.
4. Once within that dialog box, click the Install/Uninstall tab.
5. Select E-FROST from the list of programs; then click the Add/Remove button.
6. A final warning will ask if the user want to delete E-FROST from your computer. If this is the case, click Yes to remove all E-FROST files.

STARTING E-FROST

To start the program, click on E-FROST program name available from the Windows Start menu.

Main Form

When the E-FROST program is opened, a blank form with file menu and inactive tool buttons in the top left corner of the interface appears as shown figure 25.

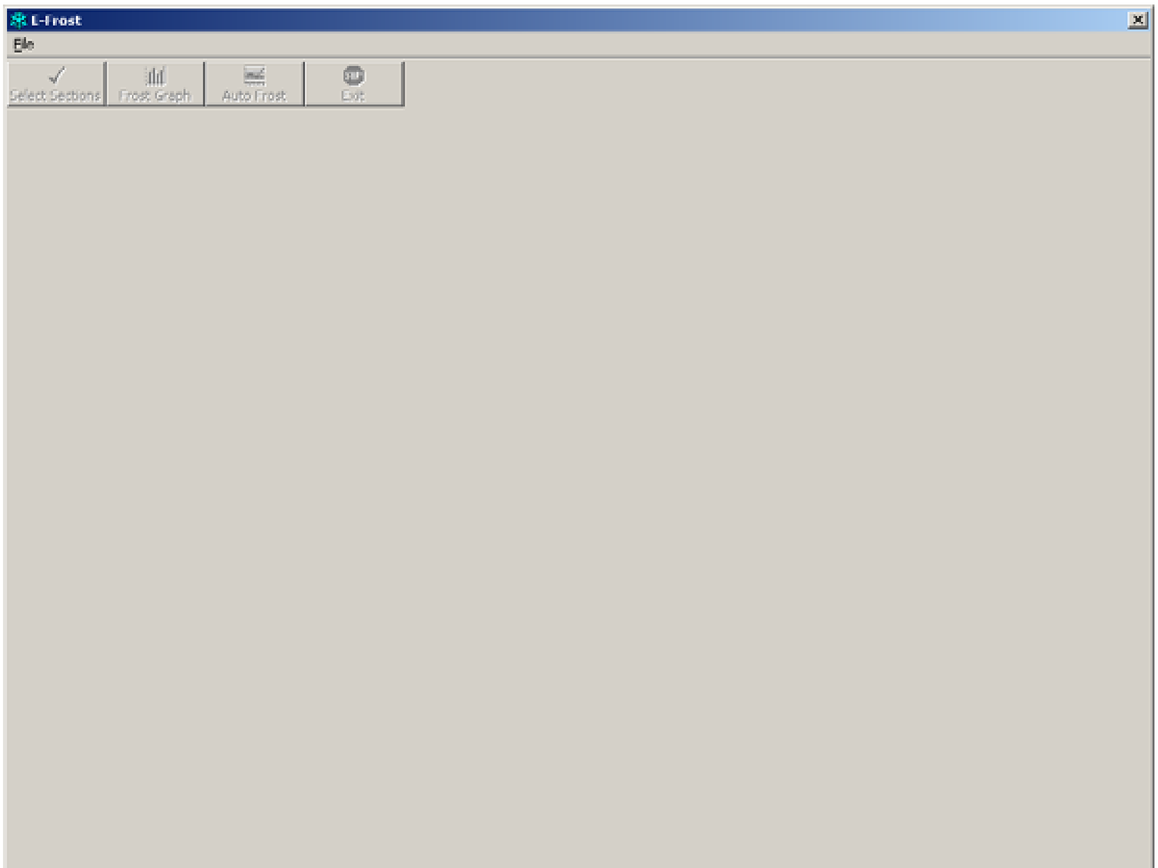


Figure 25. Screen capture. Opening screen in E-FROST.

There are four tool buttons in E-FROST that help navigate between screens and provide different program functions. These tool buttons are located on the left side of the screen and are shown in figure 26. Each button's function is described below the figure.

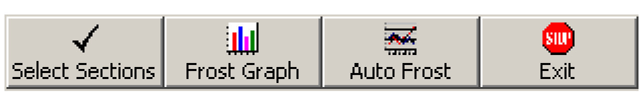


Figure 26. Screen capture. Tool buttons.

Select Sections

The Select Sections tool button allows the user to choose a site for analysis from a list that is linked to the database.

Frost Graph

The Frost Graph tool button shows the frost graph after all missing temperature data and all temperature data between -1 ^{o}C and 0 ^{o}C have been reviewed. The Frost Graph button will be inactive until all review has taken place and the frost graph has been finalized.

Auto Frost

The Auto Frost tool button displays the frost graph with the original data set from the database, before any review has taken place.

Exit

The Exit tool button safely closes the E-FROST program.

Load Database

To run E-FROST analyses, the analysis database needs to be loaded first. The analysis database contains preprocessed temperature, ER, and moisture data for the SMP sites. To load a database, click File > Open Database, as shown in figure 27. A dialog box appears, prompting the user to open the database, as shown in figure 28. After locating and selecting the database, click the Open button located in the bottom right portion of the dialog box.

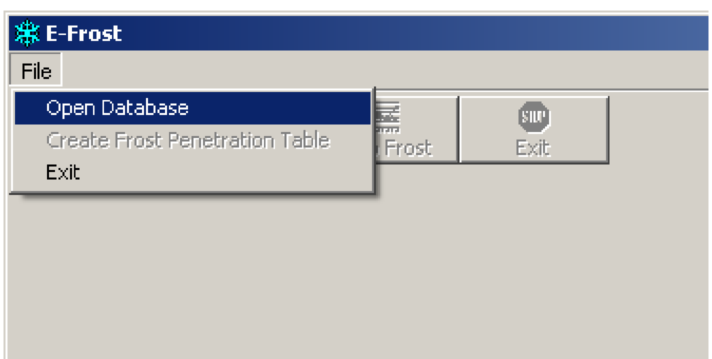


Figure 27. Screen capture. Open database.

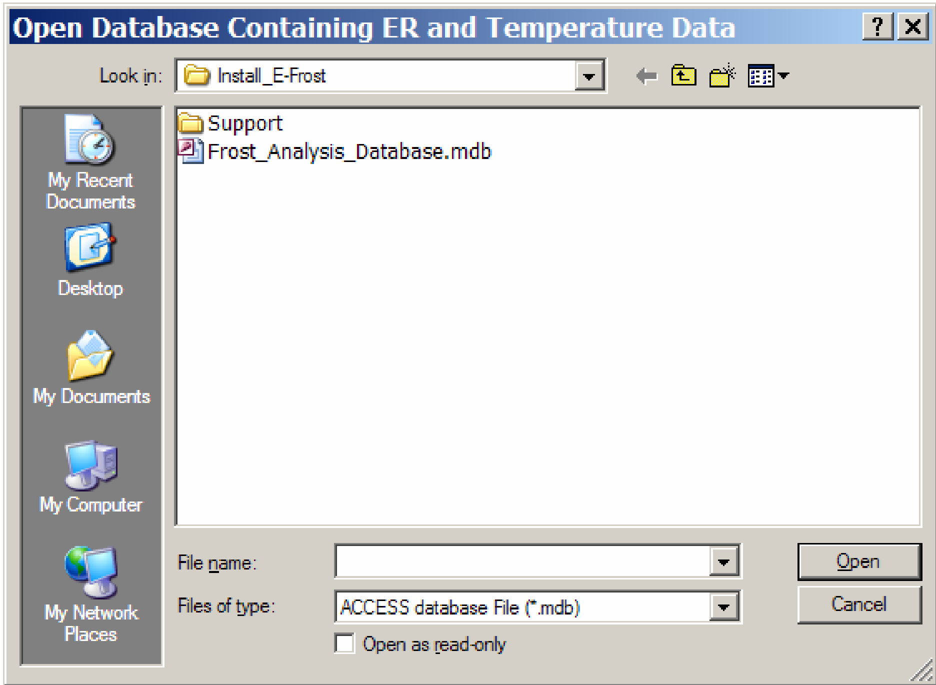


Figure 28. Screen capture. Locate the database containing SMP data.

Select Analysis Table

Once the analysis database is uploaded, the E-FROST analysis table selection window will appear as shown in figure 29.

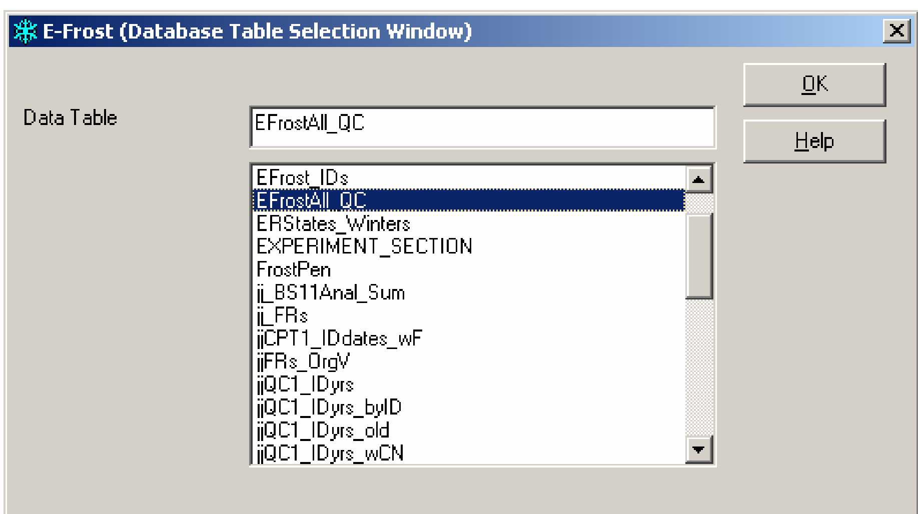


Figure 29. Screen capture. Select data table for analysis.

Select the table with the SMP site data, which is EFrostAll_QC and click OK to complete the database linking process. Once the database is connected to the program, the Select Sections and Exit user buttons will become active (figure 30).

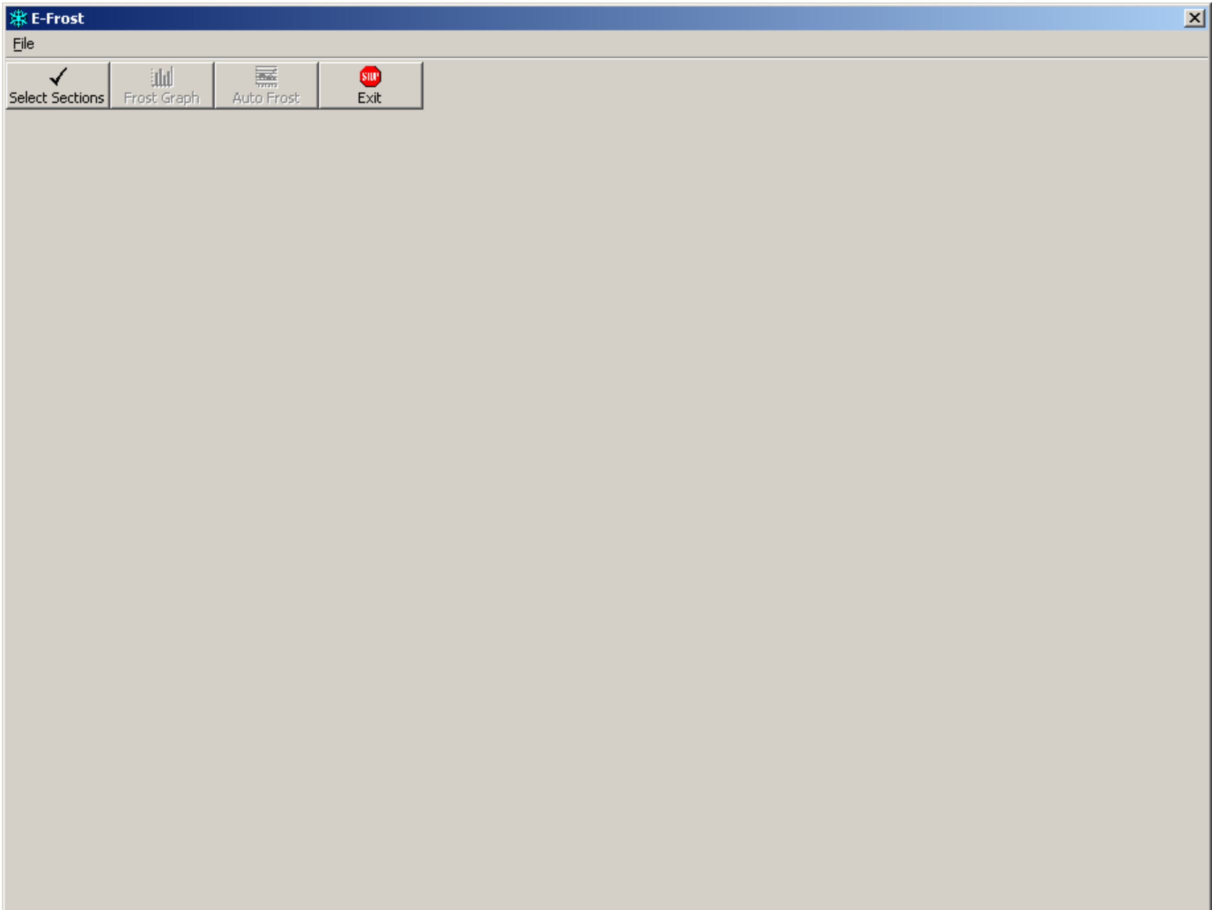


Figure 30. Screen capture. Frost linked to database with some tool buttons activated.

Select SMP Site

To select an SMP site for analysis, click the Select Sections tool button. A Section Selection window will appear containing a list of available SMP sections for analysis, as shown in figure 31. Click an SMP section name and then click OK. In the following example SMP site 46-0804-1 was selected for analysis. The last digit in section ID represents LTPP construction number.

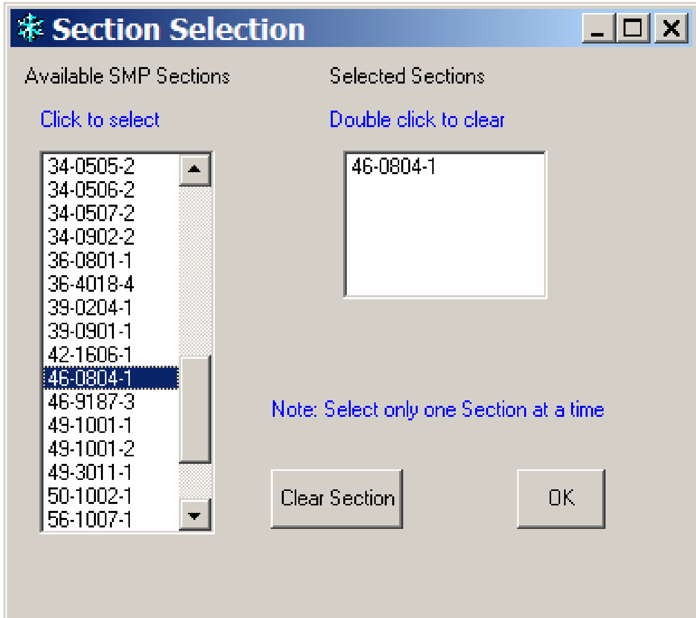


Figure 31. Screen capture. SMP Section window.

E-FROST ANALYSIS OPTIONS

Frost Penetration Analysis Form

A blank Frost Penetration Analysis form becomes visible once an SMP site is selected for analysis, as shown in figure 32. If more than 2 years of data (730 days) are available for the site, a warning message will appear to prompt the user to select a shorter time period. The MinDate and MaxDate fields on the form indicate the range of the available data. Above the minimum and maximum dates are the text boxes where the user can enter date ranges for review. The user can move between different years of frost data by using the buttons to the right (to progress forward) or the left (to move backward) of the default user date range. The user can also manually enter the beginning and ending dates of interest by typing over the values in User Date boxes and clicking the Plot New button.

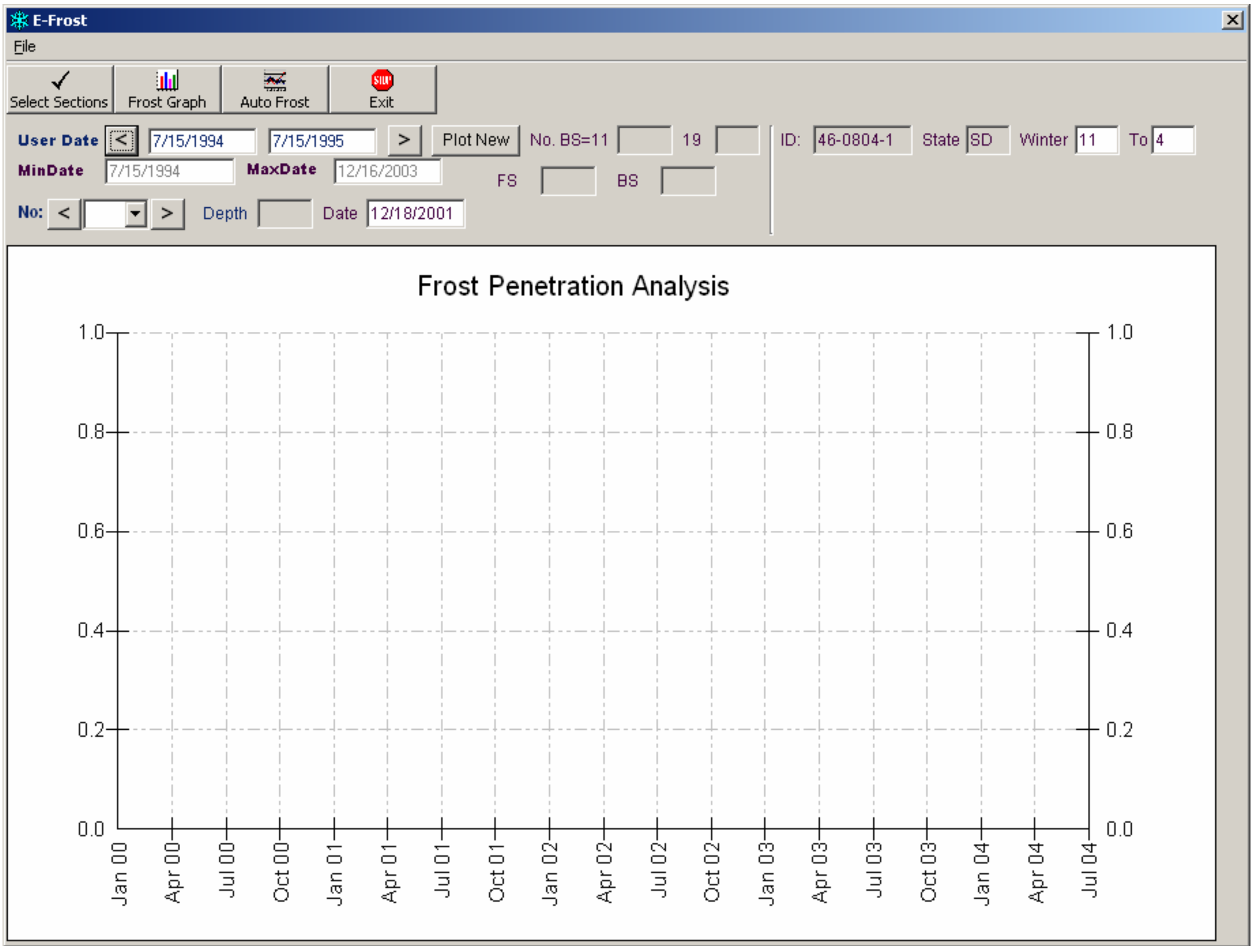


Figure 32. Screen capture. Blank Frost Penetration Analysis screen.

Review Auto Generated Frost Profile

Clicking on the Auto Frost tool button results in a generation of temperature-based frost penetration profile, as shown in figure 33. In this example, the automated frost penetration profile was generated for SMP Site 46-0804 for the winter season of 1999–2000. The profile consists of a grid with the horizontal axis displaying different SMP dates on a daily scale and the vertical axis displaying different analysis depth based on ER probe depths. Each cell is color-coded to provide information about freeze state at a given date and at a given depth, as indicated in table 11. In addition, black “X”s are used to indicate data points missing temperature data.

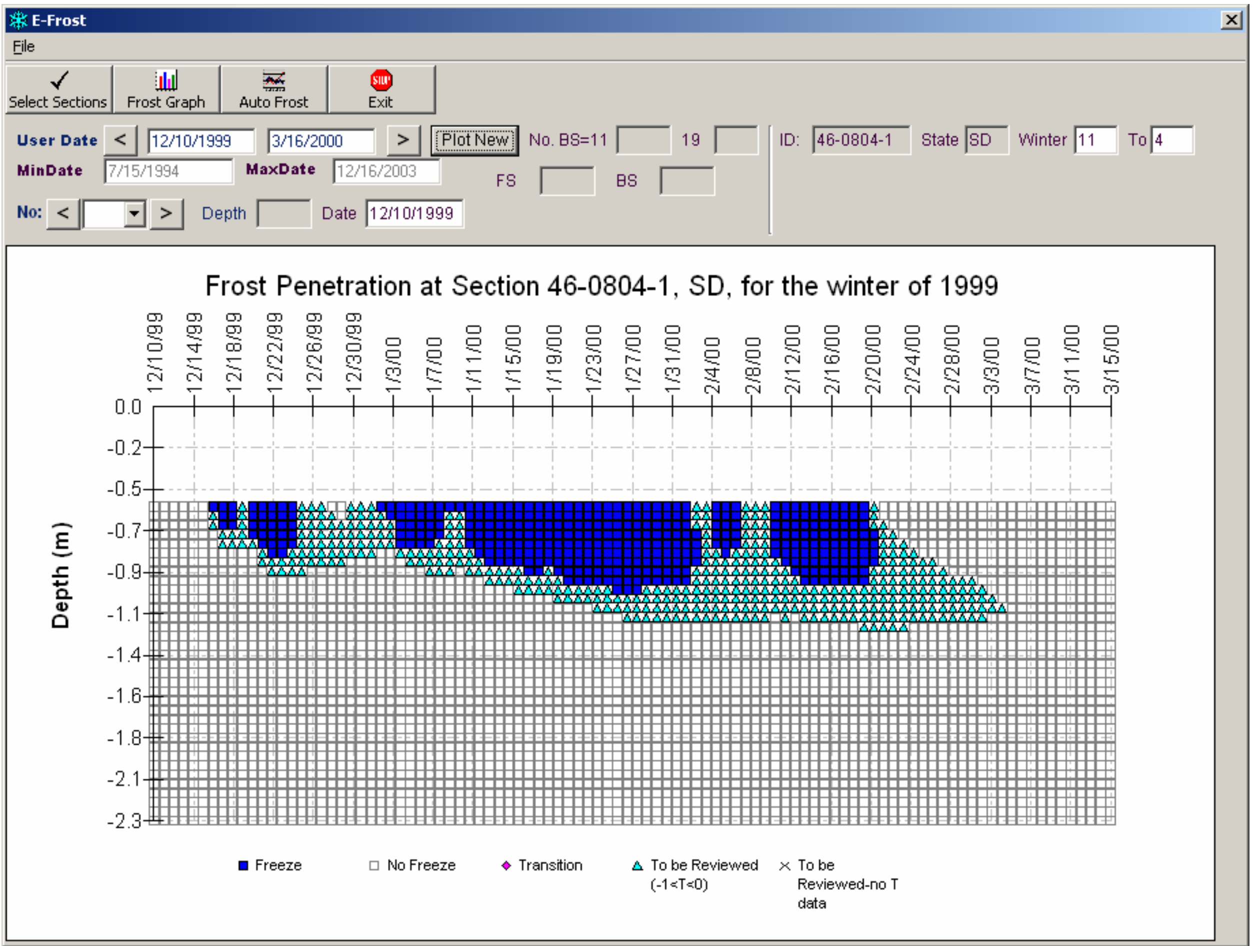


Figure 33. Chart. Automatically generated frost penetration profile at SMP site 46-0804 for the winter of 1999.

Table 11. Freeze state and frost depth chart color coding.

Color code	Shape	Assigned freeze state	Subsurface temperature	Analyst's action
Blue	Rectangle	Freeze	T < -1 ^{o}C	Assigned automatically; however, the analyst has an option to change the state to transitional (pink) or no-freeze (white) upon data review
White	Rectangle	No freeze	T > 0 ^{o}C	Assigned automatically; however, the analyst has an option to change the state to transitional (pink) or freeze (blue) upon data review
Light blue	Triangle	Review	T < 0 ^{o}C and T > -1 ^{o}C	Assigned automatically; however, the action is required from analyst to manually review the data and change the state to freeze, no-freeze, or transitional
Pink	Diamond	Transitional	Near FR	This color is assigned upon analyst review of all supporting data when it is not clear whether or not soil is frozen (partially frozen case)

The AutoFrost algorithm automatically assigns the state of subsurface freeze condition at each electrode location using the following rules:

- The 0 ^{o}C freezing isotherm is used as the low boundary to define the no-freeze state. No-freeze is automatically assigned to all points with a temperature above 0 ^{o}C (white cells).
- A value of -1 ^{o}C is used as an upper boundary to define the freeze state. Freeze is automatically assigned to all points with a temperature below -1 ^{o}C (blue cells).
- All data that fall between two boundaries are flagged for manual review to determine the appropriate freeze state based on ER, temperature, and moisture trend analysis (light blue triangles).

Review Time Series Data

The light blue triangles on the AutoFrost profile graph indicate that the analyst must review the data and change the freeze state in the analysis table as appropriate. To aid in this analysis, E-FROST creates a time-series plot of ER, temperature, and moisture content changes. The plot is brought up to the screen once the analyst clicks on the light blue triangle cell. Similar plots can be brought up for review by clicking on any other cell on the frost penetration profile chart.

To review temperature, ER, and moisture time-series trends for a selected measurement depth, (1) identify measurement depth on left vertical axis in the frost penetration profile plot, then (2) click on any cell in the automated frost penetration graph for a selected depth value depth to bring up the time series graph (see the example shown in figure 34). Use the "<" and ">" buttons next to the No. label on the form to review the time series at different depths, or select the desired depth from the dropdown menu.

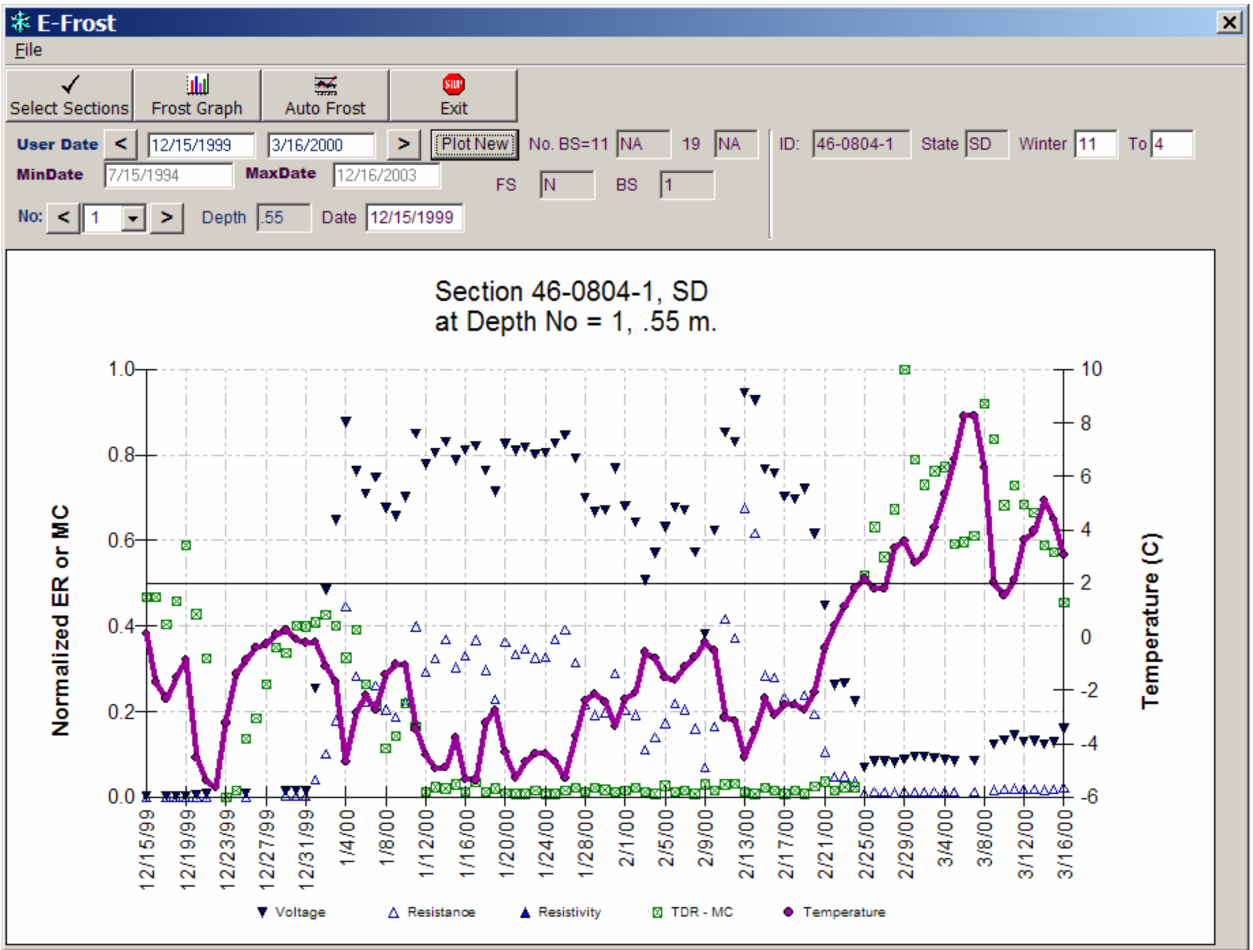


Figure 34. Chart. Time series plot for SMP site 46-0804 for the winter of 1999 at analysis depth = 0.55 m (1.8 ft).

Review Revised Frost Penetration Profile

Upon completion of the trend analysis and assignment of freezing conditions, an updated frost penetration plot can be reviewed by clicking on Frost Graph tool button, as shown in figure 35.

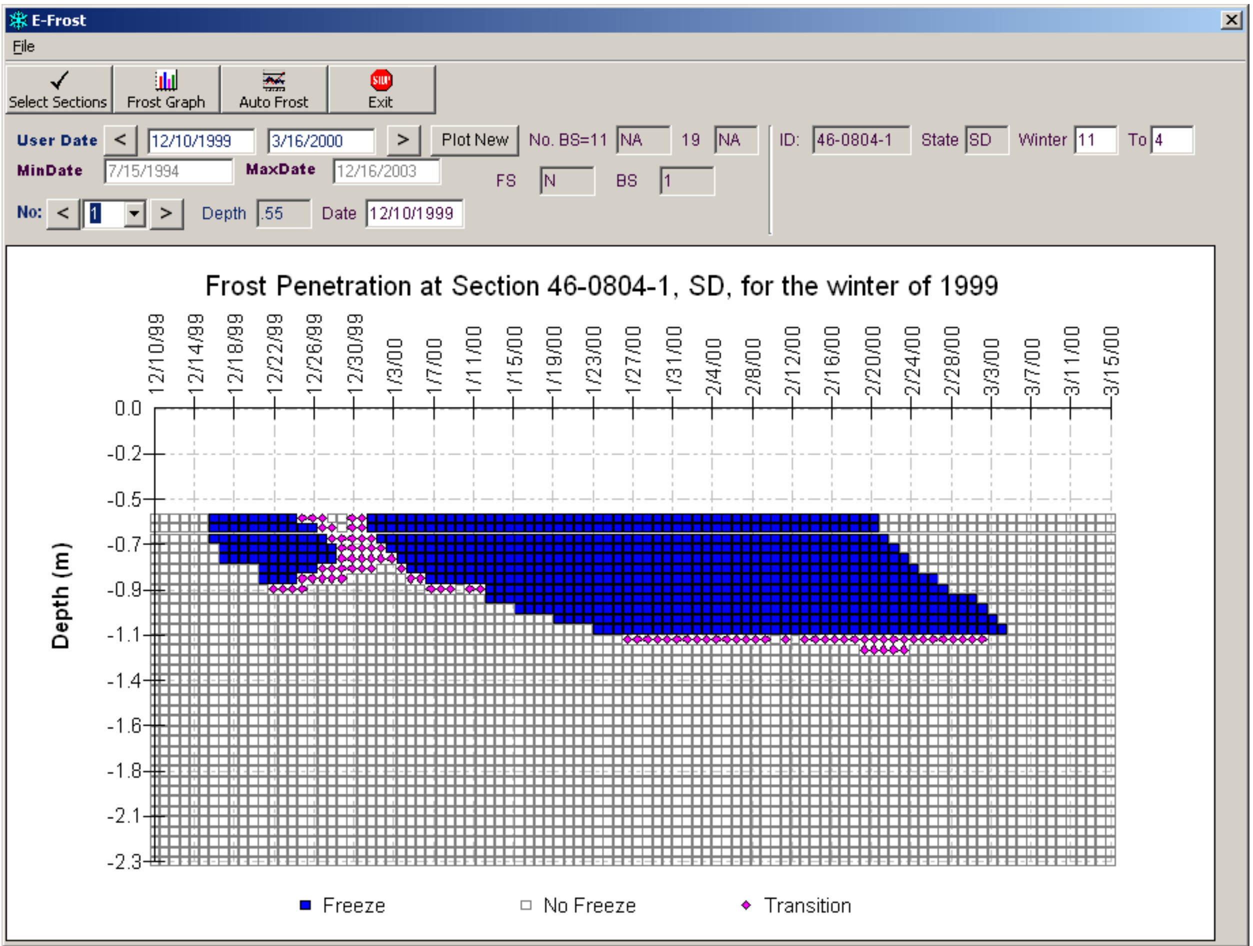


Figure 35. Chart. Final frost penetration profile for SMP site 46-0804 for the winter of 1999.

View Previously Processed Data

After the analysis of all sites is complete and all frost penetration profiles are finalized, the user can select any previously analyzed SMP site and view the frost penetration profiles at that site. To view previously processed data, click the Select Sections tool button and select an SMP site. Next, click the Frost Graph tool button to see the final frost penetration profile of the selected site. From the Frost Graph screen, the user can click on any cell to view the time series graph at selected depth. To view automatically generated frost penetration profile, click the Auto Frost tool button. To exit the program, click Exit on the tool bar.

GENERATE FROST PENETRATION TABLE

To generate the frost penetration table FrostPen, click File > Create Frost Penetration Table, as shown in figure 36.

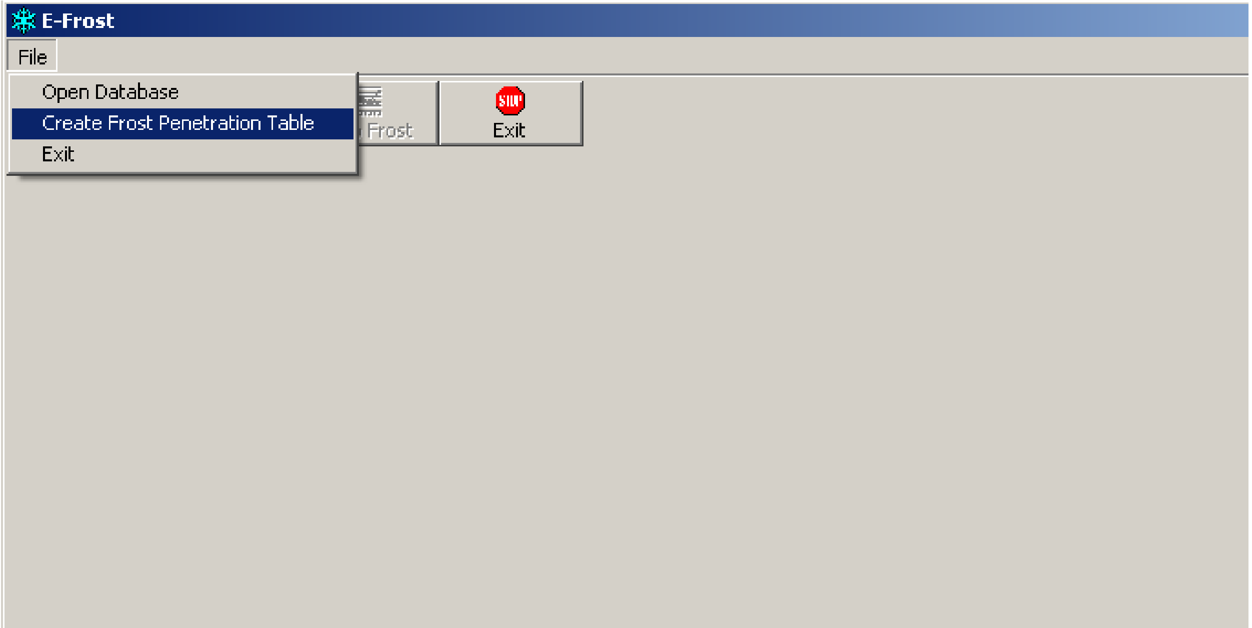


Figure 36. Screen capture. Create Frost Penetration Table option.

APPENDIX B. EICM MODELING INPUTS

Table 12. EICM inputs.

Site_ID	**16_1010**	**23_1026**	**27-4040**	**27_6251**	**31_3018**	**34_0506**	**34_0902**	**36_0801**	**39_0901**	**46_0804**	**46_9187**	**50_1002**	**56_1007**
Start Year	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996
Start Month	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.	Sept.
Length Analysis Period (day)	3195	3287	3287	3287	3287	3287	3287	3287	3287	3287	3287	3287	3287
Time Increment Output (hour)	1	1	1	1	1	1	1	1	1	1	1	1	1
Time Increment Calculation (hour)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Latitude (degrees. minutes)	43.4	44.34	47.18	47.27	40.4	40.17	40.43	43.21	40.38	45.56	44.46	44.07	44.3
Longitude (degrees. minutes)	-112.07	-70.17	-93.43	-94.54	-99.2	-74.51	-74.1	-77.55	-83.07	-100.25	-102.03	-73.1	-108.55
Short-wave absorptivity	0.8	0.75	0.8	0.9	0.8	0.8	0.8	0.95	0.8	0.8	0.8	0.8	0.9
Upper limit freezing (°F)	32	32	32	32	32	32	32	32	32	32	32	32	32
Lower limit freezing (°F)	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2
Pavement Layer 1													
Material	Asphalt	Asphalt	PCC	Asphalt	PCC	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt
Thickness (inches)	5.2	9.8	8.1	9	11.9	9.7	12.4	4.9	19.7	7.2	5.9	8.5	2.8
Number of elements	5	10	8	9	12	10	12	5	20	7	6	9	3
Thermal Conductivity (BTU/hr-ft-°F)	0.67	0.67	1	0.67	1	0.67	0.67	1.5	1.5	0.67	0.67	0.67	0.67
Heat capacity (BTU/lb-°F)	0.22	0.22	0.2	0.22	0.2	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Unit Weight (pcf)	148	148	150	148	150	148	148	148	148	148	148	148	148

Table 12. EICM inputs—continued.

Site_ID	16_1010	23_1026	27-4040	27_6251	31_3018	34_0506	34_0902	36_0801	39_0901	46_0804	46_9187	50_1002	56_1007
Pavement Layer 2													
Material	Asphalt												
Thickness (inches)	5.7												
Number of elements	6												
Thermal Conductivity (BTU/hr-ft-°F)	0.67												
Heat Capacity (BTU/lb-°F)	0.22												
Unit Weight (pcf)	148												
Soil Layer 1													
Material	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a	A-1-a
Thickness (inches)	12	17.6	6	10.2	5.6	10	5	8.4	6	12	11	25.8	6.8
Number of Elements	12	17	6	10	5	10	5	9	6	12	11	26	6
Porosity	0.25	0.25	0.25	0.3	0.25	0.25	0.25	0.25	0.25	0.25	0.1	0.25	0.24
Saturated permeability (ft/hr)	0.0583	0.0583	0.0583	0.0583	0.0583	0.0583	0.0583	0.0583	0.0583	0.0472	0.0416	0.138	0.074
Dry unit weight (pcf)	127	127	127	127	127	127	127	127	127	127	127	127.2	127.1
Dry thermal conductivity (BTU/hr-ft-°F)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	1.6	0.8	0.8
Dry heat capacity (BTU/ft^3-°F)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Table 12. EICM inputs—continued.

Site_ID	16_1010	23_1026	27-4040	27_6251	31_3018	34_0506	34_0902	36_0801	39_0901	46_0804	46_9187	50_1002	56_1007
Initial VMC (%)	15.26	15.26	15.26	2	15.26	15.26	15.26	15.26	15.26	15.26	8	15.08	15.07
Fredlund–af	7.2555	7.2555	7.2555	7.2555	7.2555	7.2555	7.2555	7.2555	7.2555	7.05034	6.94777	7.33241	7.29231
Fredlund–bf	1.234	1.234	1.234	1.234	1.234	1.234	1.234	1.234	1.234	1.28391	1.29552	1.69057	1.41089
Fredlund–cf	0.83152	0.83152	0.83152	0.83152	0.83152	0.83152	0.83152	0.83152	0.83152	0.83784	0.83536	0.81675	0.82058
Fredlund–hr	117.4	117.4	117.4	117.4	117.4	117.4	117.4	117.4	117.4	152.2	169.6	108	113.6
Plasticity Index (PI)	1	1	1	1	1	1	1	1	1	152.2	4	1	1
D60 (mm)	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82	10.82
Passing #4 (%)	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.7	44.76.8
Passing #200 (%)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	4	
Soil Layer 2													
Material	A-2-4	A-2-4	A-2-7	A-2-4	A-2-4	A-2-4	A-1-a	A-2-4	A-7-5	A-7-5	A-6	A-2-4	A-2-4
Thickness (inches)	300	300	300	300	300	300	5	300	12	300	300	300	300
Number of Elements	150	150	150	150	150	150	5	150	12	150	150	150	150
Porosity	0.27	0.29	0.14	0.29	0.26	0.27	0.25	0.27	0.39	0.38	0.36	0.27	0.27
Saturated permeability (ft/hr)	0.0004.39	0.000792	1.55E-06	1	0.00364	0.000439	0.04	0.000439	4.28E-06	3.29E-06	1.95E-05	0.000439	0.00326
Dry unit weight (pcf)	123.4	120.2	120.8	119.8	124	123.4	127	123.4	102	104.8	107.9	123.4	123.1
Dry thermal conductivity (BTU/hr-ft-°F)	0.8	0.8	0.8	3	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Dry heat capacity (BTU/ft^3-°F)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Initial VMC (%)	18.39	19.65	12	19.77	17.88	18.39	15.26	18.39	32.69	31.24	39.57	18.39	18.54
Fredlund–af	9.28522	10.2125	76.5824	5.74545	5.85556	9.28522	7.2555	9.28522	125.312	117.641	108.409	9.28522	13.4953

Table 12. EICM inputs—continued.

Site_ID	16_1010	23_1026	27-4040	27_6251	31_3018	34_0506	34_0902	36_0801	39_0901	46_0804	46_9187	50_1002	56_1007
Fredlund–bf	0.643865	0.3	0.926038	1.95497	1.8823	0.643865	1.234	0.643865	0.57723	0.621817	0.68007	0.643865	0.567768
Fredlund– cf	3.09113	3.72724	0.42491	0.71916	1.08956	3.09113	0.83152	3.09113	0.10524	0.15556	0.21612	3.09113	3.18708
Fredlund–hr	189.6	100	500	100	110	189.6	117.4	189.6	500	500	500	189.6	160
Plasticity Index (PI)	2	0	14	0	1	2	1	2	24	19	16	2	1
D60 (mm)	0.3216	0.3216	5.73	2	0.3477	0.3216	10.82	0.3216	0.02798	0.02798	0.05364	0.3216	0.3038
Passing #4 (%)	87.2	87.2	55.4	87.2	87.2	87.2	44.7	87.2	94	94	93.5	87.2	87.2
Passing #200 (%)	22.4	22.4	27.4	10	5	22.4	8.7	22.4	70.5	70.5	63.2	22.4	30
Soil Layer 3													
Material							A-2-4		A-7-5				
Thickness (inches)							300		300				
Number of Elements							150		150				
Porosity							0.27		0.39				
Saturated permeability (ft/hr)							0.000439		4.28E-06				
Dry unit weight (pcf)							123.4		102				
Dry thermal conductivity (BTU/hr-ft-°F)							0.8		0.8				
Dry heat capacity (BTU/ft^3-°F)							0.22		0.22				
Initial VMC (%)							18.39		32.69				
Fredlund–af							9.28522		125.312				
Fredlund–bf							0.643865		0.57723				
Fredlund–cf							3.09113		0.105242				

Table 12. EICM inputs—continued.

Site_ID	16_1010	23_1026	27-4040	27_6251	31_3018	34_0506	34_0902	36_0801	39_0901	46_0804	46_9187	50_1002	56_1007
Fredlund–hr							189.6		500				
Plasticity Index (PI)							2		24				
D60 (mm)							0.3216		0.02798				
Passing #4 (%)							87.2		94				
Passing #200 (%)							22.4		70.5				
Deep ground temperature (°F)	51	48.1	40.88	40.55	51.43	53.74	55.25	47.85	54	44.87	48.13	46.4	46.03

1 inch = 25.4 mm

32 °F = 0 °C (Deduct 32, then multiply by 5, then divide by 9).

Note: For soil layers, The Fredlund Soil Water Characteristic Curve model is used to relate soil suction to water content. Fredlund parameters a_f and h_r have units of psi. Parameters of b_f and c_f are unitless. Parameter a_f is a measure of air entry, the soil suction at which the soil becomes less than 100-percent saturated. Parameters b_f and c_f determine the rate of change of moisture content versus suction as it transitions from saturated to unsaturated (no free water). h_r defines the slope of the curve after free water is removed.

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