COMPUTEDPARAMETERS

Freeze/Thaw Monograph for LTPP

Introduction

To study the effect of freezing/thawing conditions on pavement performance, data from three electrical resistivity (ER) measurements (resistivity, resistance, and voltage) are collected approximately every month, every other year at selected Seasonal Monitoring Program (SMP) sections. In addition, soil temperature data are collected daily. An interactive procedure was developed and used to interpret ER and temperature data and to derive the freeze state and frost penetration parameters. The data are contained in two tables: **SMP_FREEZE_STATE** and **SMP_FROST_PENETRATION**. The **SMP_FREEZE_ STATE** table characterizes the freeze state as frozen or non-frozen at each measurement depth. **SMP_FROST_PENETRATION** translates the freeze state at each measurement depth into starting and ending depths of frozen layer(s).

Benefits

The data collected to monitor freezing and thawing in Long Term Pavement Performance (LTPP) seasonal monitoring test sections are stored in the form of electrical voltage, current readings, soil electrical resistance (two-point contact), and soil ER (four-point contact). These data cannot be used directly for any analysis concerning seasonal frost and thaw changes in pavement systems.

The data in table **SMP_FROST_PENETRATION** are the end product of an analysis of the raw data to determine the boundaries of frozen layers within the pavement cross-section. These computed parameters will be useful, indeed necessary, in any analysis looking at the structural aspects of the seasonal monitoring test sections. The data in table **SMP_FREEZE_STATE** are the results of

intermediate steps in the interpretation process. As such, they will be of interest and use to those wishing to understand or revisit the process by which the results presented in table **SMP_FROST_PENETRATION** were derived.

Process Implementation

The following LTPP Information Management System (IMS) tables are used in creating the data in **SMP_FREEZE_STATE:**

- **SMP_ERESIST_AUTO**
- **SMP_ERESIST_MAN_4POINT**
- **SMP_ERESIST_MAN_CONTACT**
- **SMP_ERESIST_DEPTHS**
- **SMP_MRCTEMP_AUTO_DAY_STATS**
- **SMP_MRCTEMP_DEPTHS**

Interpretation of ER data is performed using a graphical interactive procedure that was developed specifically for analyzing LTPP data. The **SMP_FREEZE_STATE** data are used in the derivation **SMP_FROST_PENETRATION**, along with a software program developed for project use (FROST).

FROST is an interactive program that displays freeze state-related data in a graphical form. The program includes a set of built-in logical statements that will define the freeze state of a soil, given the user-defined threshold line for the three ER measurements. For each section, the user selects the threshold value for each of the 35 depths for ER measurements. Once the

threshold values are entered, the program displays a time-series plot of frost penetration in the given section.

The user can click on any point in the graph and view ER and temperature plots at that specific depth and testing day. The user can also enter a different ER threshold value at each depth to examine the effect of changing the threshold line on the frost penetration profile. Data are saved when the user moves to the next observation depth (electrode) and can be retrieved at a later time.

This monograph provides a brief description of the program and the analysis steps.

Analysis Steps

The determination of the freeze state using ER and soil temperature data may be described in terms of three steps: (1) preprocessing, (2) processing, and (3) smoothing. A brief description of each follows. It should be noted that more details can be found in *Determination of Frost Penetration in LTPP Test Sections—Final Report*, FHWA-RD-99088.

Pre-Processing

Data from six IMS tables are used in the analysis. The following computations are carried out to produce the required intermediate variables:

- Compute measurement depth (the average depth

of the electrodes used in the measurements). It is noted that each voltage and contact resistance measurement is performed using two electrodes, and each resistivity measurement is performed using four electrodes.

- Compute average resistance, resistivity, and voltage for testing day and measurement depth.

- Query contact resistance, resistivity, and voltage for matching section, date, and measurement depth. The query should be designed to return all available records where at least one ER measurement is available.

- For each measurement depth, normalize resistivity, resistance, and voltage with respect to their extreme values. For instance, normalized resistivity may be computed according to the following formula:

$$R_{N,i} = \frac{R_i - R_{min,i}}{R_{max,i} - R_{min,i}}$$

where:
$R_{N,i}$ = Normalized resistivity, at measurement depth i.

R_i = Actual resistivity taken at measurement depth i.

$R_{min,i}$ = Minimum resistivity value measured at depth i.

$R_{max,i}$ = Maximum resistivity value measured at depth i.

The normalized contact resistance and voltage can be obtained in a similar fashion. It should be noted that the actual and normalized ER values are linearly related and the normalization process does not "distort" the ER profile.

- Interpolate the average soil temperature at each ER measurement depth. As shown in figure 1, the measurement depths of ER probes do not match those of thermistor probes.

To obtain the temperature at the ER measurement depth (as shown in the schematic), the following linear interpolation formula was used:

$$T_i = T_1 + (T_2 - T_1) * \frac{X}{L}$$

where:

T_i = Interpolated temperature.

T_1 = Temperature at the upper thermistor.

T_2 = Temperature at the lower thermistor.

X = Distance from the ER measurement depth to the upper thermistor.

L = Distance between the two thermistors.

- If the same-day temperature is missing, then use temperature within 2 days. Use the following hierarchy to select available temperature data:

Temperature Substitution Hierarchy

First Preference —
Same-day temperature.

Second Preference —
Previous-day temperature.

Third Preference —
Next-day temperature.

Fourth Preference —
Temperature from 2 days ago.

Fifth Preference —
Temperature from 2 days later.

- Determine cold winter months for each section based on historical temperature. Cold winter months will be used to confirm ER peaks only if temperature data are missing. Cold winter months are defined as those months in which a freezing temperature (at or below 0°C) was measured in the top unbound pavement layer.
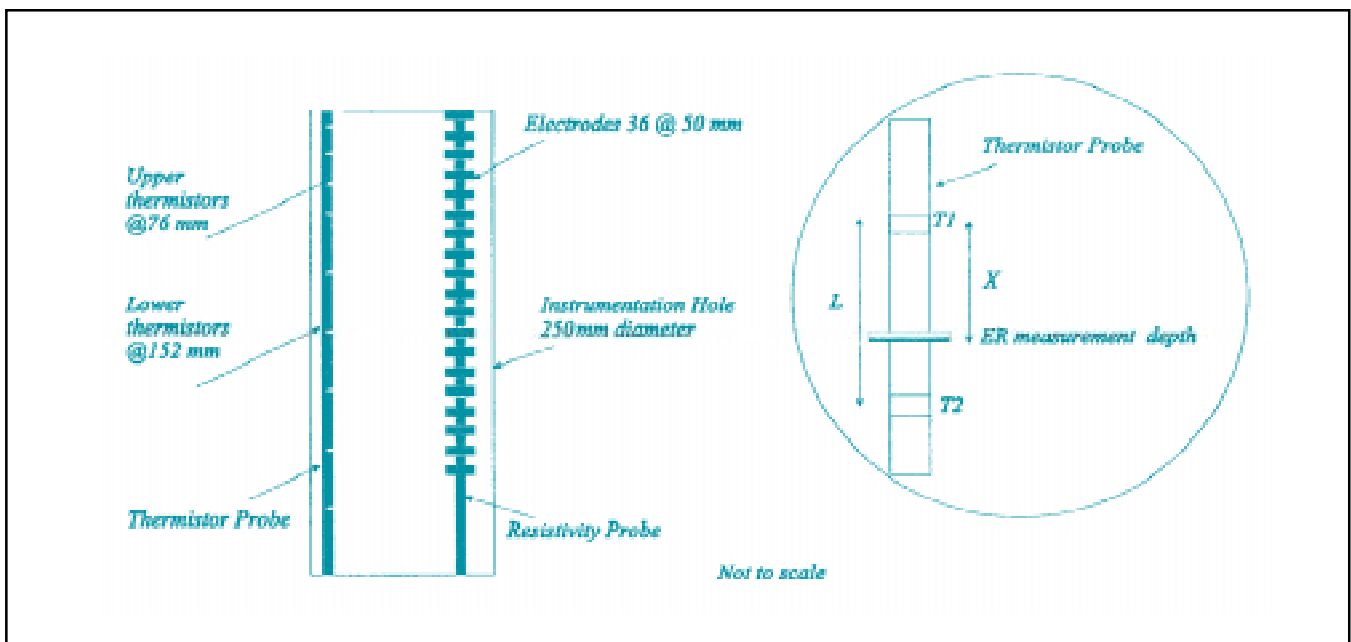

Figure 1. Schematic diagram of the arrangement of thermistor and resistivity probes.

Processing Using FROST
Once the data are prepared and saved in a specific format, FROST may be used to determine the freeze state and frost penetration. As mentioned earlier, FROST requires user interaction to determine the soil freeze state. The user must input an ER threshold line that is to separate freezing from nonfreezing conditions. The threshold value is defined as a value at the ER normalized scale that is likely to distinguish between frozen and unfrozen conditions. ER values greater than the threshold value represent frozen conditions and vice versa. Guidelines on placing the ER threshold line are presented later. Based on these values, FROST determines the freeze state according to the decision tree shown in figure 2.

Smoothing the Frost Profile
In some cases, FROST determines a frost profile that may consist of thin layers of ice lenses and thawed pockets of soil. Although this may not be uncommon, it is possible that highly irregular frost profiles may be caused by noisy data. In addition, it is recognized that thawing and freezing often occur gradually, possibly forming transitional freeze state zones. However, current ER data do not seem precise enough to enable reliable identification of such a transitional state. As such, the current method of ER data interpretation uses a "freeze/no-freeze" designation, with the inherent assumption that the transitional freeze state could
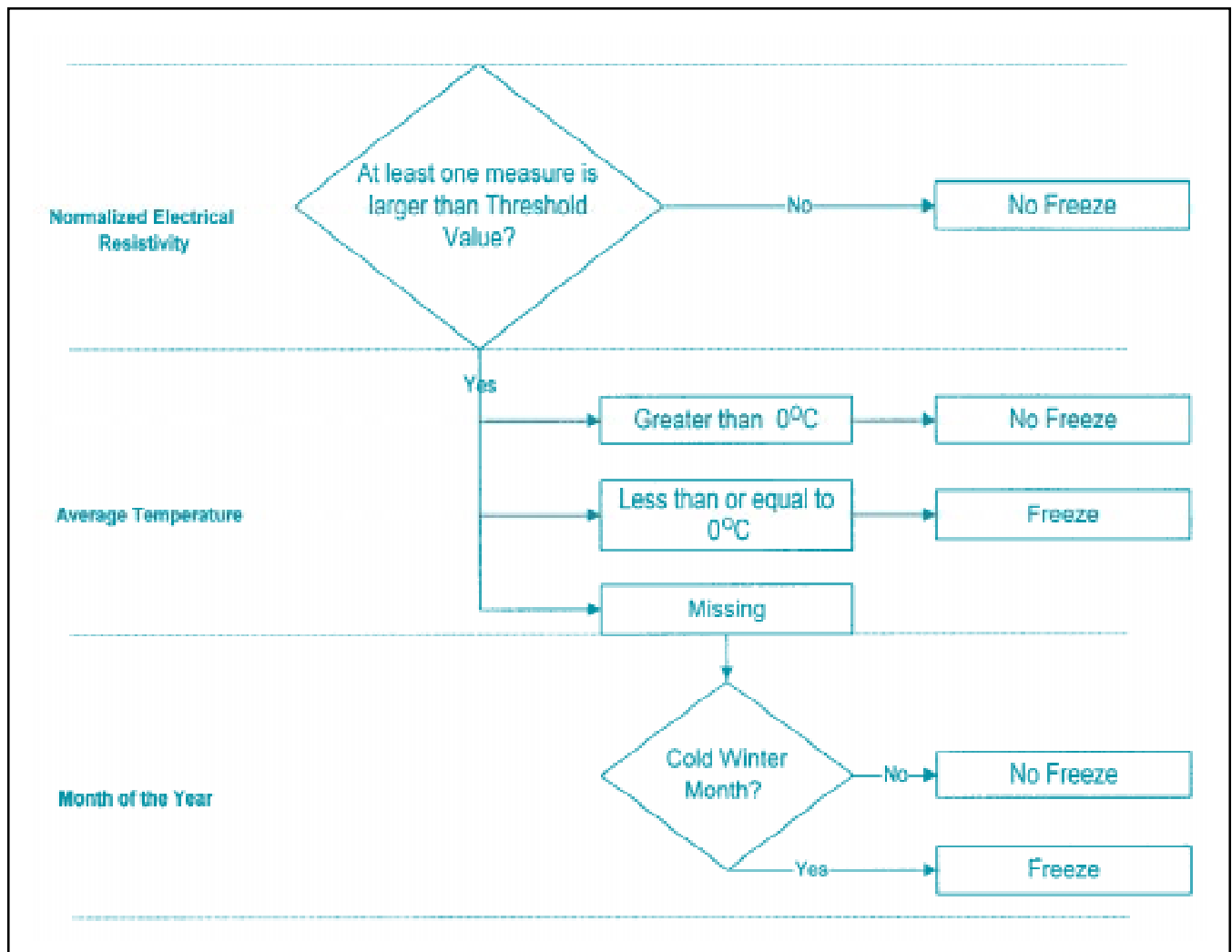

Figure 2. Frost decision tree.

be assigned to either freeze or no-freeze based on the overall frost profile.

ER probes are placed approximately 50 mm apart depthwise. Therefore, the layer thickness resolution for freeze state determination is 50 mm. However, from a structural engineering perspective, a 50-mm-thick layer of thawed soil between two thick frozen layers is very likely to be ignored, given the resolution of current structural analysis techniques. Based on these considerations, the data analysis team recommends smoothing the frost profile as illustrated in figure 2.

- After using time-series ER plots to define the threshold line at the 35 measurement depths, FROST will display the frost penetration profile. The user should inspect the frost penetration profile and they can manually change the freeze state at any location on the graph. If the freezing condition at a particular point is in disagreement with 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 could be forced to agree with that of the surrounding soil. In addition to the option of manually changing the freeze state, FROST includes an option to "smooth" the

frost profile obtained at any given date.

- Selecting the automated smoothing option will invoke a procedure that starts from the top down, comparing the freeze state at each point with those of the points above and below it. If the freeze state is different from these two points, the freeze state at the point under consideration will be changed to agree with that of surrounding points. This procedure is executed for all points, except the top point. Smoothing the frost penetration profile will only eliminate layers less than 100 mm thick.

Guidelines for Defining the ER Threshold Line in FROST

This concept involves drawing a threshold line that separates peak ER values from the rest of the data. An ER peak is a relatively large ER value that occurs in cold temperature and winter months. Peaks are not consistent in their absolute values from one year to another. Therefore, the threshold line must account for all potential peaks for multi-year data. The program places a vertical line through each point having the right condition for freezing, according to temperature or season. These points should be inspected carefully since the user input will affect only these points. All other data

points are automatically considered unfrozen, regardless of the user input.

The user should inspect the marked points and ensure that they are all above the threshold line. Marked points that do not show an ER peak (i.e., their ER values are not significantly larger than those of non-winter points) should not be placed above the threshold line, especially if placing such points above the threshold line may result in lowering the line such that non-winter readings will fall above the threshold line (which would violate the definition of the threshold line).

Tips
The analyst should be aware of the following:

- It does not matter how low or how high the threshold line is, as long as it separates the peaks from the rest of the data. In many cases, the user has some flexibility in placing the threshold line to achieve the same results.

- Points midway between peaks and valleys should be included with peaks, as long as they occur in the winter months. In this way, temperature will determine the freeze state for such observations.

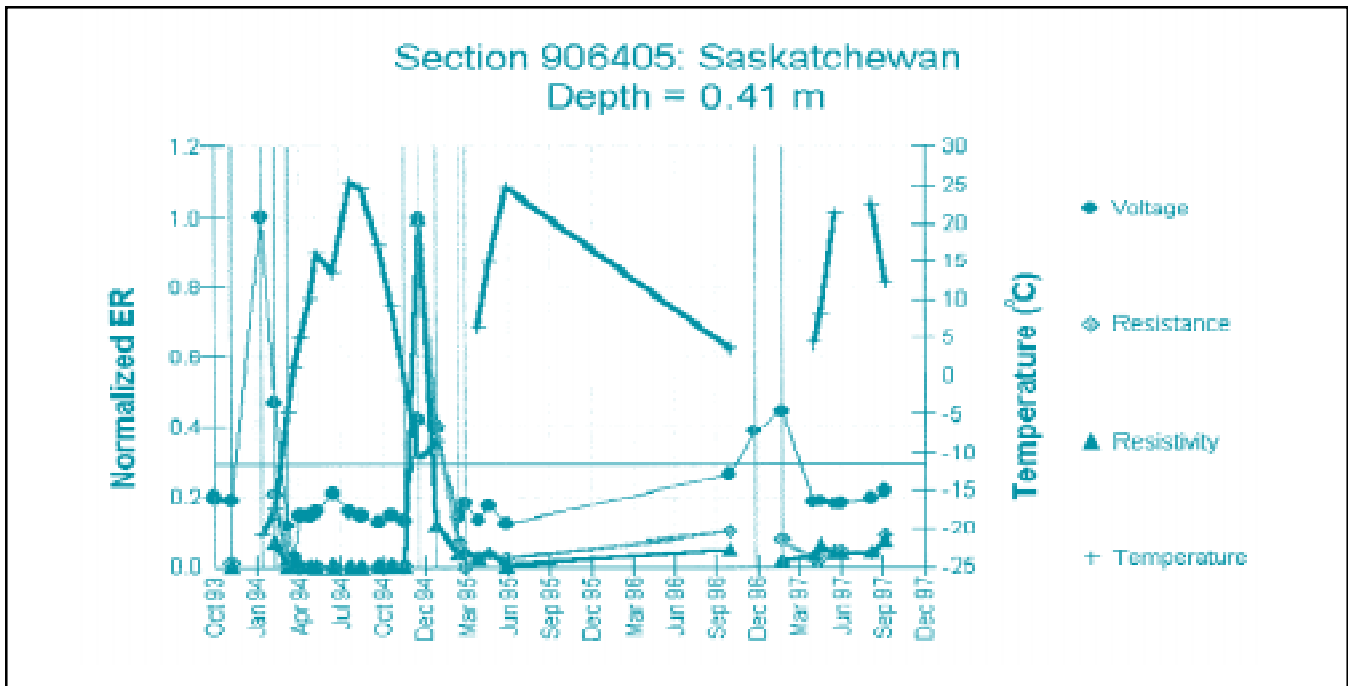- It does not matter if one, two, or all three of the ER measurements are above

Figure 3. Example ER time-series graph produced by FROST.

the threshold line. If any measurement is above the line, it will be considered a candidate for the freezing condition. In most cases, the peaks of ER values are at different magnitudes. Therefore, the user does not need to place all ER peaks for a given date above the threshold line.

• Points located near the threshold line (especially at a freeze temperature) should be examined for discontinuity. If the freezing condition at that particular point is in disagreement with surrounding points, then the threshold line may be moved to produce more consistent results.

Example

Figure 3 above, shows an example plot used in the freeze state determination. The plot represents a time-series of normalized ER measurements and temperature for Saskatchewan section 906405, about 0.4 m below the pavement surface. Based on temperature and season, there are four incidents of possible freezing in the winter of 1993/1994, five in the winter of 1994/1995, and two in the winter of 1996/1997. These incidents are marked by a vertical line.

The user first attempts to place all marked points above the line. As indicated earlier, only the upper ER peak needs to be placed above the line. For

instance, in the last possible freezing incident marked by the rightmost vertical line in the graph, the line passes through three points: voltage (upper curve), resistance, and then resistivity (lowest value). Only the upper peak for voltage needs to be placed above the threshold line.

It can be seen that some of the marked points do not show an ER peak and cannot be placed above the threshold line without bringing the line too low. Such points are left below the line, indicating a no-freeze condition. The threshold value for this example is approximately 0.3.