Sensor Technology for Decision Support of Spring Load Restrictions

Xinbao Yu, Nina Liu, Xiong (Bill) Yu, and Ning Li

Spring load restrictions (SLR) are commonly used as a pavement preservation strategy in regions of the United States where pavements are constructed in freeze–thaw environments. Similar practices are used by many other countries. Enforcement of SLR has huge economic impacts to the cost of pavement maintenance and freight industry. Thus, improving the decision support for the start and end of SLR has significant economic implications. To enforce SLR, agencies need to know when the weakening of unbound pavement layers caused by thaw begins and ends. A few technologies are available to directly and indirectly measure the thawing status; however, they have shortcomings in terms of complexity, reliability, and cost. This paper introduces new innovatively designed sensors that can assist the decision support of SLR. These sensors are accurate, inexpensive, and automatic.

BACKGROUND

Spring Load Restrictions

SLRs are developed in response to the weakening of pavement substructure in the thaw period. During the spring, pavement layers generally are in a saturated, weakened state because of partial thaw conditions and trapped water. The pavement strength may be reduced by as much as 50% of typical fall strength (1, 2). This results in increased damage and a shorter useful life unless the loads are reduced. In an analysis conducted by Washington State Department of Transportation of state, city, county, and regional engineers, freeze–thaw together with frost heaving and excessive moisture were among the most important factors in causing road deterioration (on average, 40%). Thirty percent of the route system was reported to be experiencing seasonal structural weakening (3). The problem of spring thaw can be alleviated by designing the pavement base using frost-resistant standards and limiting capillary actions. However, this design can be very expensive. As a result, SLR is adopted by many counties as a cost-effective protective measure (Table 1).

Existing Technology and Practice for SLR

Given the important performance and economic implications of SLR, properly applying SLR, that is, the setting of proper restriction period and restriction level, is critical to ensure that the desired function is achieved. The critical time for SLR is when the pavement first thaws and the stiffness of the base layer is low. Thus, proper measurement and prediction of freeze–thaw events are crucial for developing a successful load-restriction strategy.

A few technologies are available to provide such information (Table 2). Examples include those based on temperature and resistivity probes. These technologies, however, are not reliable, and the data collection is time-consuming. Relative indicators of pavement strength may be obtained from load tests such as the falling weight deflectometer (FWD). These tests provide deflection data, which are indicative of pavement strength or the strength values can be calculated from the deflection data. FWD testing has its limitations in that it has no predictive value. Spring thaw can occur very rapidly, depending on the weather conditions. FWD testing, however, provides no data except the deflections.

Application of SLR in the United States has largely been based on deflection measurement and experience. In addition, there is no systematic strategy to control the level of load restrictions (Table 3). To simplify the load-restriction decision, Minnesota Department of Transportation used a policy of using the actual and predicted average daily temperature to determine timing of SLR. The duration

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Transportation Research Record: Journal of the Transportation Research Board, No. 2053, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 17–22. DOI: 10.3141/2053-03

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was placed at fixed 8 weeks. Given the importance of the SLR on pavement performance, a more reliable decision support is necessary (4–6). This paper introduces innovative designs of freeze–thaw sensor that can accurately monitor the extent of thaw process. A strong relationship between degree of thaw and material strength could enable the implementation of SLR with sound scientific support.

**Time Domain Reflectometry**

Time domain reflectometry (TDR) uses the propagation of an electromagnetic wave to measure material properties. It works by generating a small-magnitude electromagnetic field excitation and measuring the material response. By using a fast-rising pulse of a few picoseconds by the current electronics, TDR measures the broad frequency band material responses from a few megahertz to gigahertz. The information commonly used from a TDR signal is the reflection points, which are related to the speed of electromagnetic wave in the soil and are subsequently used for determining the apparent dielectric constant \( K_a \) and the long-term signal level, which is related to the energy attenuation and subsequently used to determine the electrical conductivity \( E_{C_a} \) (Figure 1). Both quantities can be easily obtained from a TDR signal. The dielectric constant and electrical conductivity are strongly related to the physical and mechanical properties of materials (7).

Earlier generations of TDR electronics (such as Tektronix 1502B) used to be cumbersome and required high power consumption. They are only suitable for laboratory use. With the advances in the electronics industry, high-performance, compact TDR devices are becoming available at affordable cost. The current TDR electronics have the advantages of being relatively inexpensive, being capable of generating high-quality signal, requiring low power consumption, and allowing for flexible data communication (by either Serial or Ethernet communication protocol). An example is TDR100 manufactured by Campbell Scientific, Inc. The unit cost is approximately $3,500, and it can simultaneously monitor eight locations with the aid of a multiplexer (cost approximately $500). More locations can be simultaneously monitored through the use of multiple multiplexers. Because TDR uses metallic waveguide as the sensing components, TDR probes can be designed to be sufficiently rugged and durable for field installation and monitoring purposes (7).

TDR is an established technology for soil instrumentation in geotechnical engineering. It can be used to determine volumetric water content, soil moisture, hydraulic conductivity, and relative density of soils and sediments. TDR is a non-destructive, non-invasive method that can be used to monitor changes in soil properties over time.

### TABLE 1 Benefit of Pavement Life from Load Restrictions for the United States (1)

<table>
<thead>
<tr>
<th>Pavement Load Reduction During Thaw (%)</th>
<th>Expected Increase in Pavement Life (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>62</td>
</tr>
<tr>
<td>30</td>
<td>78</td>
</tr>
<tr>
<td>40</td>
<td>88</td>
</tr>
<tr>
<td>50</td>
<td>95</td>
</tr>
</tbody>
</table>

### TABLE 2 Status of SLR in European Counties (2)

<table>
<thead>
<tr>
<th>Country</th>
<th>Start of SLR</th>
<th>End of SLR</th>
<th>Restriction</th>
<th>Technology for Determining Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>n/a</td>
<td>n/a</td>
<td>2.5-, 4-, 6-, 8-ton for single dual tire axles</td>
<td>Frost depth measurements</td>
</tr>
<tr>
<td>Finland</td>
<td>April</td>
<td>May</td>
<td>Gross weights 4-, 8-, 12-, 18 ton; total shutdown</td>
<td>FWD, experience</td>
</tr>
<tr>
<td>Iceland</td>
<td>30 cm of thaw</td>
<td>n/a</td>
<td>Depends on vehicle type and axle configuration</td>
<td>Frost depth measurements</td>
</tr>
<tr>
<td>Sweden</td>
<td>April</td>
<td>May</td>
<td>4-, 6-, 8-ton per axle</td>
<td>FWD, frost depth measurements, experience</td>
</tr>
<tr>
<td>Norway</td>
<td>5–15 cm of thaw Prediction</td>
<td>Min. 90% of summer bearing capacity 4–8 weeks after imposing</td>
<td>Changes yearly as needed</td>
<td>FWD, frost depth measurements</td>
</tr>
</tbody>
</table>

### TABLE 3 SLR in Six U.S. States

<table>
<thead>
<tr>
<th>State</th>
<th>Start of SLR (around)</th>
<th>End of SLR (around)</th>
<th>Restriction</th>
<th>Technology for Determining Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dakota</td>
<td>March 15</td>
<td>June 1</td>
<td>Differs between trunk highways and county roads</td>
<td>Deflection measurement and experience</td>
</tr>
<tr>
<td>South Dakota</td>
<td>February 28</td>
<td>April 27</td>
<td>6-, 7-ton per axle</td>
<td>Deflection measurement and experience</td>
</tr>
<tr>
<td>Iowa</td>
<td>March 1</td>
<td>May 1</td>
<td>No overloads</td>
<td>Road Rater and experience</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>March 10</td>
<td>May 10</td>
<td>No overloads</td>
<td>Deflection measurement and experience</td>
</tr>
<tr>
<td>Michigan</td>
<td>Every March</td>
<td>Late May</td>
<td>70% of gross weight for HMA roads</td>
<td>Experience</td>
</tr>
<tr>
<td>Minnesota</td>
<td>March</td>
<td>May</td>
<td>5-, 7-, 9-ton per axle</td>
<td>Design testing and experience</td>
</tr>
</tbody>
</table>

content (8) because water has a much larger dielectric constant (approximately 81) than that of the air (approximately 1) or soil solids (approximately 3 to 5). Recent development of new procedures and equipment has significantly improved the accuracy of TDR method for water content determination and extended it to include estimation of in situ soil density (7, 9, 10). TDR principles are explored in this paper to develop sensors that assist SLR decisions.

**EVALUATION OF TDR SENSOR FOR FREEZE–THAW MONITORING**

As the first step in the new sensor development, experiments were conducted to validate the ability of TDR for monitoring the freeze–thaw cycle in soil. One type of fine sand and one type of lean clay (CL) were selected for this evaluation program. The soil samples were prepared at approximately their optimal water content and were then compacted into a standard compaction mold. A new temperature sensor with embedded processor iButton was installed in the soil specimen to measure the temperature (Figure 2a). The mold was then covered with a plastic sheet and placed into the freezer (Figure 2b). TDR software was started to automatically take readings at 10-min intervals. After the soil was completely frozen, it was taken out from the freezer and placed at room temperature to initialize the thaw process. TDR monitoring program was again activated to monitor the signal change during the thawing process.

Figures 3 and 4 summarize the TDR-monitored dielectric constant during the freeze–thaw process. Also plotted on the figure is the measured electrical conductivity (inverse of resistivity) during the freeze–thaw process. As shown in these figures, different stages of freeze–thaw can be clearly identified from the evolution curve of TDR measured dielectric constant. The change of dielectric constant is attributed to the change of the physical status of soil water. (Free water has a dielectric constant of approximately 81. By contrast, the dielectric constant of ice is approximately 4.) The following concepts
(Equations 1 and 2) were introduced to characterize the degree of freeze–thaw directly from TDR measurement (11):

\[
\text{freeze(\%)} = \left( \frac{w_{\text{unfrozen}} - w_i}{w_{\text{frozen}} - w_{\text{frozen}}} \right) \times 100\% \\
= \sqrt{K_{\text{unfrozen}}} - \sqrt{K_{\text{frozen}}} \times 100\%
\]

where freeze(\%) = percentage of freeze,  
\( w_{\text{unfrozen}} \) and \( K_{\text{unfrozen}} \) = gravimetric water content and dielectric constant of sample in complete frozen status,  
\( w_i \) and \( K_{i} \) = gravimetric water content and dielectric constant at time \( t \) of the freeze–thaw sample, and  
\( w_{\text{frozen}} \) and \( K_{\text{frozen}} \) = gravimetric water content and dielectric constant in completely frozen sample.

Similarly, the concept of percentage of thaw can be defined in Equation 2,

\[
\text{thaw(\%)} = \left( \frac{w_{\text{thaw}} - w_{\text{thaw}}}{w_{\text{frozen}} - w_{\text{frozen}}} \right) \times 100\% \\
\quad = \frac{\sqrt{K_{\text{unfrozen}}} - \sqrt{K_{\text{thaw}}}}{\sqrt{K_{\text{free}}} - \sqrt{K_{\text{unfrozen}}}} \times 100\% 
\]

where \( w_{\text{thaw}} \) and \( K_{\text{thaw}} \) are the water content and dielectric constant in complete thaw status, respectively.

With the concept defined, the degree of freeze–thaw can be readily determined from TDR measured dielectric constant (Figure 4). During the freeze–thaw cycle, the degree of freeze and degree of thaw are related by the following equation:

\[
\text{thaw(\%)} = 1 - \text{freeze(\%)}
\]

**INFLUENCE OF FREEZE–THAW STATUS ON SOIL MATERIAL BEHAVIORS**

The previous investigation shows the TDR sensor provides accurate characterization of the freeze–thaw status. This principle was incorporated into the experimental program to investigate the effects of freeze–thaw on soil behaviors. A hollow tube TDR sensor was fabricated to provide nondestructive measurement of prepared soil specimen (Figure 5).
CONCLUSIONS AND DISCUSSIONS

Proper implementation of SLR calls for innovative instrumentation that can accurately determine the freeze–thaw status. The current field instrumentation methods, which are mostly based on measuring the soil temperature or electrical resistivity, have limitations in identifying the details in the freeze–thaw stages. They can thus at best serve as an indicator of completely frozen or completely thawed status. This paper shows TDR technology can accurately identify the various stages of freeze–thaw process (such as the beginning and ending point of freeze–thaw process and the percentage of water transition between liquid and solid status). All have important engineering implications. The degree of freeze–thaw can be directly calculated from TDR measured dielectric constant. The TDR instrument is inexpensive and rugged. The whole process of signal acquisition and analyses can be automated easily.

Another important application of this technology is to assist in a more systematic investigation on soil behaviors during the freeze–thaw process. Although extensive research has been conducted on frozen soils, the current knowledge on soil behaviors during the freeze–thaw process is limited. A few factors could have contributed to this status, including the requirement of sophisticated experimental control. Accurately determining the extent of freeze–thaw in soils is another challenging issue, which could not be achieved with commonly used technologies. The innovative TDR instrument introduced in this paper could play an important role to advance the study on soil behaviors during freeze–thaw process.

With more knowledge accumulated on the effects of freeze–thaw on soil mechanical properties, a more rugged SLR program can be implemented to optimize the load level restrictions based on the actual status of soil behaviors. The authors are collaborating with the Minnesota Department of Transportation to conduct a full-scale field evaluation program at Mn/Road, the world’s largest and most comprehensive outdoor roadway laboratory. On further refinement, this technology has great potential to bring important economic benefits for pavement maintenance as well as for the freight industry.

ACKNOWLEDGMENTS

The authors thank Roger Green of Ohio Department of Transportation for providing information on current practice in freeze–thaw measurement. The assistance of engineers at Minnesota Department...
of Transportation, including Ben Worel, Jack Herndon, Robert Strommen, Doug Lindenfelser, in installing prototypes on MnRoad is highly appreciated.

REFERENCES


The Seasonal Climatic Effects Including Frost Action on Transportation Infrastructure Committee sponsored publication of this paper.