Identifying frost-susceptible areas on Finnish railways using the ground penetrating radar technique

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Identifying frost-susceptible areas on Finnish railways using the ground penetrating radar technique

Mika Silvast¹, Antti Nurmikolu², Bruce Wiljanen¹ and Matti Levomäki³

Abstract
In Finland, the railway is a vital transportation system. A large quantity of raw materials, goods and passengers are transported on mixed traffic tracks. Due to freeze–thaw cycles, differential frost heave can affect the track performance and results in speed restrictions. The maintenance of winter-related problems on heavy haul railway lines is expensive and causes difficulties for the flow of rail traffic. In order to make maintenance cost-effective and sustainable it is essential to identify the problem areas and determine their causes. During the last decade the ground penetrating radar (GPR) technique has proven to be an effective and non-destructive method to measure railway structures and various material properties. This paper presents and discusses the key results obtained in a research project that studied the potential of the GPR method to locate track sections on Finnish railways experiencing frost problems and produce input data for preventative maintenance planning for areas at risk of developing differential frost heave. The GPR data, digital video and GPS coordinates, collected from the railway sections were combined with reference data and railway databases using the Railway Doctor software. This integrated data was then interpreted and analysed using multiple parameters specifically selected for the purpose of identifying the frost-susceptible sub-ballast structures and subgrade soils and defining the root cause of frost problems using the GPR frequency analysis techniques.

Keywords
Frost susceptibility, frost heave, ground penetrating radar, railway structures, subgrade soil

Introduction
The Finnish railway network consists of approximately 6000 km of track and plays an important role in the transport of people, goods and materials. The country is situated in a cold-climate area and the railway network is subject to frost-related problems.

In the design of the track structure, as a result of the level of smoothness required by the rails, it is desired to prevent frost damage affecting the rails. For a frost-susceptible material this would require preventing freezing of the material or blocking the passage of water into the freezing zone; neither is practical to achieve in a track structure. Therefore, the structural layers of a track (ballast, sub-ballast) are made of non-frost-susceptible materials and a sufficient thickness to prevent freezing of frost-susceptible subgrade.

Problems associated with frost action on the existing track network, which was built before current quality standards, is mainly the result of the following three reasons.

1. The thickness of non-frost-susceptible layers (ballast and sub-ballast) is insufficient to prevent the freezing of frost-susceptible subsoil.
2. Sub-ballast has been built with frost-susceptible material.
3. Ballast has become highly fouled and in turn frost-susceptible.

Frost heave problems depend on the climatic conditions. For example, the winter of 2009–2010 in Finland was unusually harsh. Speed restrictions were required on 1070 km of the 6000 kilometer line

¹Roadscanners Oy, Tampere, Finland
²Tampere University of Technology, Finland
³Finnish Transport Agency, Finland

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Corresponding author:
Mika Silvast, Roadscanners Oy, Yliopistonkatu 58 D, Tampere, 33100, Finland.
Email: mika.silvast@roadscanners.com
network in the spring of 2010 which is more than the combined total for the years 2002–2009. Proper investigation and preventative maintenance of frost problem locations can significantly reduce the amount of disturbance, such as speed restrictions, time delays, extra costs, etc., for both the track owner and user.

Sampling and laboratory analysis of soil properties has traditionally been used to study the frost susceptibility of soils. Although the samples provide valuable information, the data is from a single location and changes in material properties along the line are difficult to observe without extensive sampling. In order to efficiently analyse the mechanism of frost action, solve the cause and design the correct method of rehabilitation, continuous data such as thickness and material properties of the track structure is needed.

A research project has been performed in Finland to identify frost-susceptible areas under railway structures; in this project ground penetrating radar (GPR) measurements were taken on three different railway sections. The sections were selected from different climate zones in southern, central and northern Finland in order to study the effect of the winter season on different soil types. The total length of lines measured was 430 km. The GPR survey campaigns were performed twice, first in summer 2008 and then in winter 2009. Taking measurements in two seasons enables a comparison of seasonal changes and detection of winter-related problems such as formation of ice lenses and uneven frost action.

**Frost action**

Frost action in a soil refers to possible detrimental phenomena due to freezing and thawing, frost heave and thaw softening. The primary cause of the frost action process in areas of seasonal frost is the formation of ice lenses from water flowing from unfrozen soil into the freezing zone (Figure 1). Since the water to create ice lenses comes from unfrozen soil, the formation of ice lenses increases the volume of frozen soil. This is generally manifested at the surface of the track as detrimental frost heave. A soil material that makes ice lens formation possible is called frost-susceptible. One of the most widely accepted definitions of frost susceptibility is the one proposed by the Highway Research Board Committee on Frost Heave and Frost Action in Soil^2 which states that: ‘frost-susceptible is a soil in which significant ice segregation will occur when the requisite moisture and freezing conditions are present’. A corresponding definition has been proposed by the Technical Committee on Frost of the International Society of Soil Mechanics and Foundation Engineering.3 The frost susceptibility of a material is highly dependent on the content^4 and the quality^5 of the fines (material passes through a 0.063 mm (no. 230 USCS) sieve).

Moreover, as a condition-dependent factor, frost heave pressure must exceed the weight of structures above the soil. Conversely, it can be stated that ice lens formation will not occur if one or more of the three preconditions are not met.
The GPR technique

GPR is an effective and non-invasive tool for mapping railway structures and analysing subsurface conditions. The method provides a continuous profile of the thickness and properties of the railway structure as well as information about the subgrade soils. GPR data consists in changes in reflection amplitude, changes in arrival time of specific reflections and signal attenuation. Figure 2 presents an example of a GPR profile obtained in the railway structure survey.

The move towards non-destructive investigation methods has gained pace in recent years. GPR has shown its ability to not only determine layer thickness values\(^7\)\(^{-10}\) but also to analyse the quality of materials in the structural layers, such as the fouling of ballast.\(^11\) In addition GPR data can help to determine track subsurface conditions such as layer deformation, mud pumping, drainage problems and determination of the material quality parameters.

Data collection and preparation

GPR measurements were performed using a Geoscope\(^\text{TM}\) three-dimensional (3D) GPR system, manufactured by 3d-Radar As, including a 2.4 m wide B2431 antenna attached to a VR-Track Ltd Tka-7 maintenance engine. The 3D GPR allows measurements of several longitudinal lines at the same time and the results can be viewed as longitudinal or cross-sectional profiles or amplitude time slices.

The GPR antenna array can be lifted up to 0.5 m above the tie level and the maximum survey speed is 60 km/h (37 mile/h), depending on data collection settings. The data collection rate was controlled by a distance measurement instrument. During the survey, GPS coordinates and digital video were recorded using Road Doctor\(^\text{TM}\) Camlink software. Figure 3 illustrates the measurement set-up.\(^12\)

The processing, visualization, interpretation and analysis of the GPR data were performed using the Railway Doctor software, version 2.4 with 3D module. This software was developed especially for railway structural surveys, data analysis and rehabilitation planning. It enables the user to simultaneously view, interpret and analyse multiple data sets using the same location coordinates, e.g. GPR data, digital track video, track databases, condition measurements and maps. The possibility of data combination enables the user to conduct an integrated analysis utilizing all available data sets.

Identification of frost-susceptible materials with GPR

In order to locate frost problems, the three previously mentioned preconditions for the problems associated with frost action can be analysed using GPR measurement data. Soil types and moisture can be distinguished by analysing GPR profiles and its signal frequency spectrum. Water is the dominant factor that determines the dielectric properties of soils and if the measurements are performed during winter time, unfrozen water can be detected from the data.

GPR data includes information on layer thicknesses and material properties. The GPR signal is reflected at the interface between different structural layers. The strongest reflection occurs when the contrast between dielectric values of materials (\(\varepsilon\)) is large. The power of the reflected signal from the interface can be used to identify the material properties of the medium. An increase in water content and amount of fines increases the frost-susceptibility of the material as well the relative permittivity and electrical conductivity of the medium.

When the GPR signal travels through permeable non-frost-susceptible structural materials and encounters the frost-susceptible subgrade soil, the magnitude of the contrast between the different materials is large and this results in a clear and strong interface between layers. Figure 4 illustrates the difference between reflections from interfaces obtained from winter measurement data for the case where there is (verified with
test pit information): (a) clay subgrade soil under the sub-ballast; and (b) gravel under a sandy sub-ballast layer. By viewing the strength of the reflection in GPR greyscale profiles, the difference between different subgrade material types can be clearly seen. The sub-ballast–clay subgrade interface that has a large dielectric contrast (sub-ballast $\varepsilon_r = 7$, clay $\varepsilon_r = 30$) between materials has a strong reflection response. The sub-ballast–gravel subgrade interface has a weak response due to similar dielectric properties (sub-ballast $\varepsilon_r = 7$, gravel $\varepsilon_r = 7$).

The properties of soil materials (i.e. moisture conditions and presence of fines) can also be investigated and visualized by analysing the frequency response of the GPR signal. Fine materials and increased water content affect the frequency spectrum of the received GPR information. The windowed Fourier transform (WFT) analysis approach makes it possible to calculate the frequency response of materials in different structural layers and in subgrade soils. In the WFT analysis time-domain GPR data is transformed into frequency-domain data and parameterized by means

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**Figure 3.** The 3D GPR system installed on railway engine TKA 7 with digital video and GPS instruments (modified from Passi12).

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**Figure 4.** GPR profiles from sections with (a) clay subgrade and (b) coarse gravel subgrade soil. In both cases there is sandy sub-ballast on top of subsoil.
of a sliding calculation window in the depth and longitudinal directions. A WFT calculation algorithm can be used to generate a frequency response profile for a defined frequency frame.

In WFT profiles the GPR data is visualized as colour-coded image showing strong reflections, caused by increased moisture and fine material content in structural layers and subsoil materials. Weaker reflections indicate dry materials. The parameterized WFT profile makes it easier to locate problematic railway sections and analyse the root cause of problems. Figure 5 shows the WFT profiles for the data shown in Figure 4. Figure 5(a) shows a strong interface (shade of blue colour) between coarse sub-ballast material and frost-susceptible clay subgrade soil. On the contrary, in Figure 5(b) the interface is not visible since there is no substantial difference in electrical properties between the sub-ballast and subgrade soil materials. Nevertheless, this section does show anomalies in the sub-ballast layer which are most likely ice lenses.

Drainage and ice formation problems are possible to locate by comparing the data from different seasons. Figure 6 shows WFT profiles from a 5 km long section with different subgrade soil types that are marked along the top of the figure. The upper WFT profile is calculated from summer measurements and the lower profile from winter surveys. The summer WFT profile shows the moist areas in the sub-ballast–subgrade soil interface to a depth of 1–1.5 m in shades of blue. The winter WFT profile shows a stronger response in the same locations which indicates ice formation and increased moisture levels during winter. If strong anomalies occurring in the summer data are not visible in the winter data, then this implies that the initially detected moisture is no longer present at that location and hence ice formation cannot occur.

The WFT method also enables the calculation of the GPR data frequency response of each layer in order to estimate the frost-susceptibility of the material. The technique developed in this project, using a frost-susceptibility index (FSI), achieves this by calculating the frequency response magnitude differences of the interpreted sub-ballast and subgrade soil zones from winter and summer data.

Figure 7 presents FSI profiles from sub-ballast and subsoil, showing FSI curves and winter magnitude from the same section as presented in Figure 6.
The profile also includes the winter magnitude because FSI alone is unable to differentiate between layers if the frequency response values are similarly high or low. Table 1 illustrates the procedures used to identify frost-susceptible areas.

The classification limits used in this project were formulated for conditions in Finland. Large negative FSI values ($< -30$) indicate frost-susceptible soils and small negative values ($> -5$) represent dry or non-frost-susceptible soils.

The winter magnitude of the frequency response shows problem locations as large values ($> 30$). Low values ($10–20$) as seen from the sub-ballast layer indicate a structure which has no winter-related problems.

**Conclusions**

Railway subsurface layers are difficult to properly inspect with only visual methods or single-point sampling. GPR offers a reliable tool for track structure inspection to locate problematic areas from continuous profiles. It can effectively be used during summer to monitor moisture anomalies and fine materials and

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**Table 1. Frost-susceptibility identification using FSI profiles.**

<table>
<thead>
<tr>
<th>FSI magnitude</th>
<th>Frost-susceptibility indicator</th>
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</thead>
<tbody>
<tr>
<td>Low Low</td>
<td>Dry conditions in summer, no ice lens formation in winter $\rightarrow$ non-frost-susceptible soil</td>
</tr>
<tr>
<td>Low High</td>
<td>Wet conditions in summer, ice lens formation in winter $\rightarrow$ frost-susceptible soil</td>
</tr>
<tr>
<td>High Low</td>
<td>Wet conditions in summer, no ice lens formation in winter $\rightarrow$ non-frost susceptible soil</td>
</tr>
<tr>
<td>High High</td>
<td>Dry conditions in summer, ice lens formation in winter $\rightarrow$ frost-susceptible soil</td>
</tr>
</tbody>
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**Figure 6.** Example of WFT profiles from summer and winter measurements of a 5 km long railway section on different subgrade soils.

**Figure 7.** Example of FSI profiles including FSI curves and winter frequency response magnitude from railway section on different subgrade soils.
during the winter to provide information about sections with frost problems.

Frost-susceptible areas in structure layers or subsoil can be distinguished using the state-of-the-art GPR technique, which utilizes WFT and FSI profiles. The results give the status of the existing line and initial data for maintenance planning and rehabilitation design.

The method can be used on both heavy haul and regular traffic lines, however, due to different demands for track bed maintenance and renewal procedures, the limits for classification need to be adjusted according to the traffic type.

The use of an integrated analysis enables accurate and thus more economic rehabilitation planning measures. Other information such as track geometry data and maintenance history should be analysed with the thickness data and seasonal material quality results to further enhance the technique.

**Funding**

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