



Causes, effects and control of seasonal frost action in railways

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Received: March 12, 2013 Accepted: May 28, 2013

ABSTRACT

Seasonally cold climate and resulting frost action set great demands to railway track substructure in order to maintain track geometry. Challenges culminate on high-speed lines, where the tolerances for roughness are the tightest. Problems may result in highly increased track maintenance and need for temporary speed restrictions. The causes of frost action can be associated with subsoil, subballast or ballast. The major concern in frost protection is to avoid the freezing of frost susceptible subsoil by using sufficient thickness of subballast and relying on non-frost-susceptible subballast material. This paper provides an overview of the main research findings on the role of ballast, subballast and subsoil in frost action. In new construction the material specifications, design procedures and construction methods have been developed to ensure adequate performance of track substructures, but special challenges exist in managing existing tracks that were not designed for modern requirements. In order to perform cost-effective and sustainable track maintenance, it is necessary to recognize the problem areas and define the root-causes of problems. For locating the problem sections and defining the causes of defects, a sophisticated analysis based on integration of track geometry and ground penetrating radar (GPR) data has been developed and is summarized in this paper.

Keywords: frost action; railway track; ballast; subballast; subsoil; frost susceptibility; ground penetrating radar; track geometry; track maintenance

1 Introduction

In areas of seasonal frost, protection against frost action is a determining aspect in design and maintenance of railway track embankments. Due to safety and riding quality perspectives, the smoothness requirements for rails are increasingly strict as the operating speed increases, as indicated by European Standards (EN 13848-5:2008). The appropriate frost protection is provided by designing the thickness of non-frost-susceptible material sufficient to prevent the frost-susceptible subsoil from freezing. Based on an air-freezing index appropriate for a 50-year return period, the required combined thickness of non-frost-susceptible ballast and subballast layers is 2.0 to 2.6 m in Finland. However, as in many other countries, the majority of the existing rail network was originally built nearly a century ago. Even though the railway lines have been upgraded since then, frost protection in most of the existing lines does

not meet the above mentioned requirements. The lack of adequate frost protection causes severe track roughness problems. Therefore, for the needs of Finnish Transport Agency, Tampere University of Technology has studied the causes, effects and controlling methods of frost action extensively for a decade. The research findings are also utilized in development of data integration-based analysis tool for rehabilitation planning of frost action sites led by Roadscanners Oy.

2 Frost action mechanism

Frost action in 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 in the freezing zone by water flowing from unfrozen soil (Figure 1) (Nurmikolu, 2005). Since water contained in ice lenses

comes from unfrozen soil below, the formation of ice lenses increases the volume of freezing soil. This is generally manifested at the surface of the track as detrimental frost heave. Soil material that makes ice lens formation possible is called frost-susceptible. One of the most widely accepted definitions of frost susceptibility is by the Highway Research Board (1955) 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 is also presented in ISSMFE (1989). The frost susceptibility of a material is highly dependent on content (Nurmikolu and Kolisoja, 2008) and quality (Nurmikolu, 2010) of the fines (material passing 0.063 mm sieve).

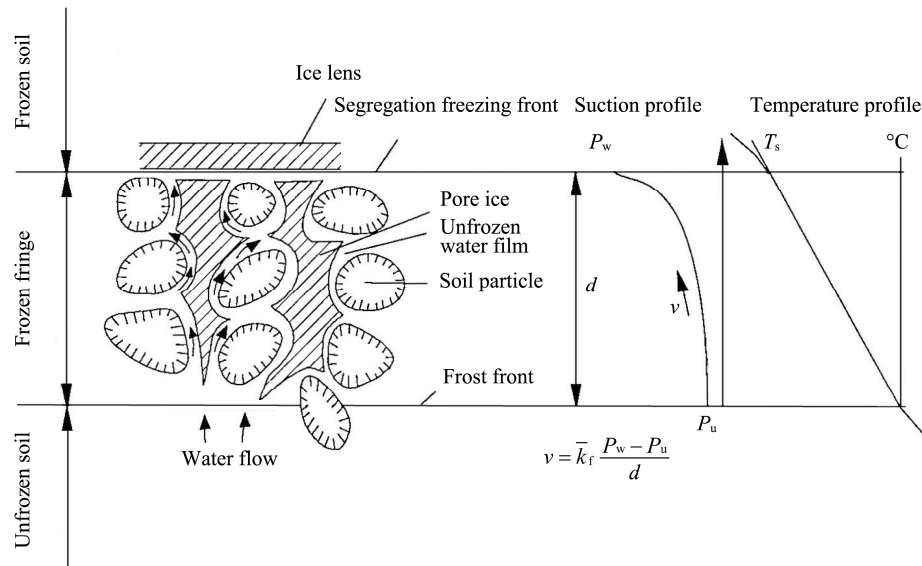


Figure 1 Concept of partly frozen zone based on the segregation potential theory (Nurmikolu, 2005)

3 Causes of frost action in railway track

Causes of frost action in railway track have been studied in laboratory scale frost heave tests (Figure 2) (Nurmikolu, 2005) and in field monitoring (Figure 3) (Pylkkänen *et al.*, 2012). In laboratory frost heave tests the main focus has been frost heave susceptibility of degraded (fouled) ballast (Nurmikolu and Kol-

isoja, 2008), subballast (Pylkkänen and Nurmikolu, 2011) and subsoil materials. Nearly 300 frost heave tests for these materials have been performed. Real-time field monitoring of frost depth, frost heave, thaw settlement, and moisture conditions is performed in 20 railway track embankments to enable modeling of frost heave in the field based on material properties determined in the laboratory and conditions (moisture, temperature) in the field.

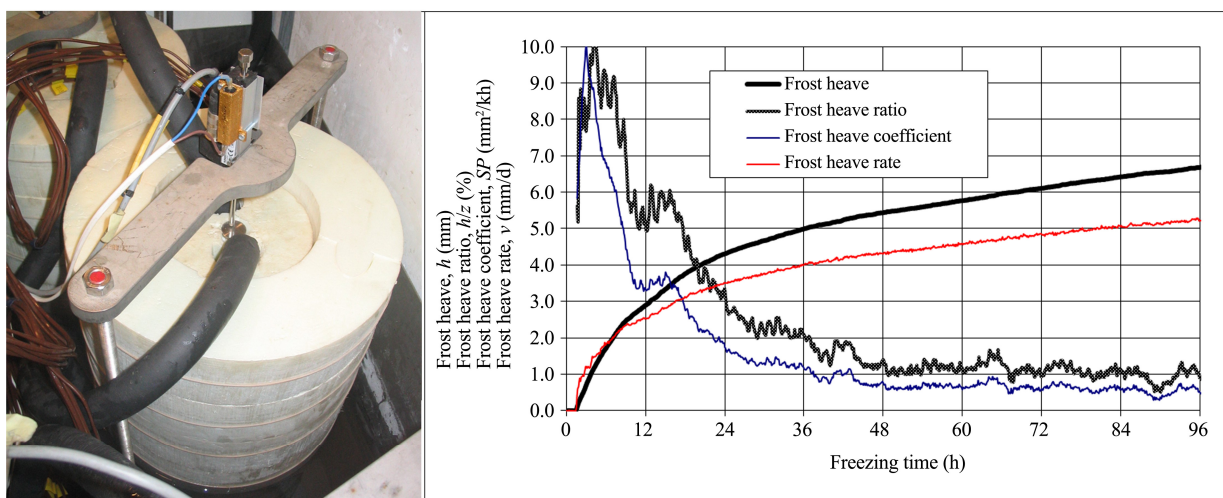


Figure 2 Laboratory frost heave test arrangement at TUT and format of test results

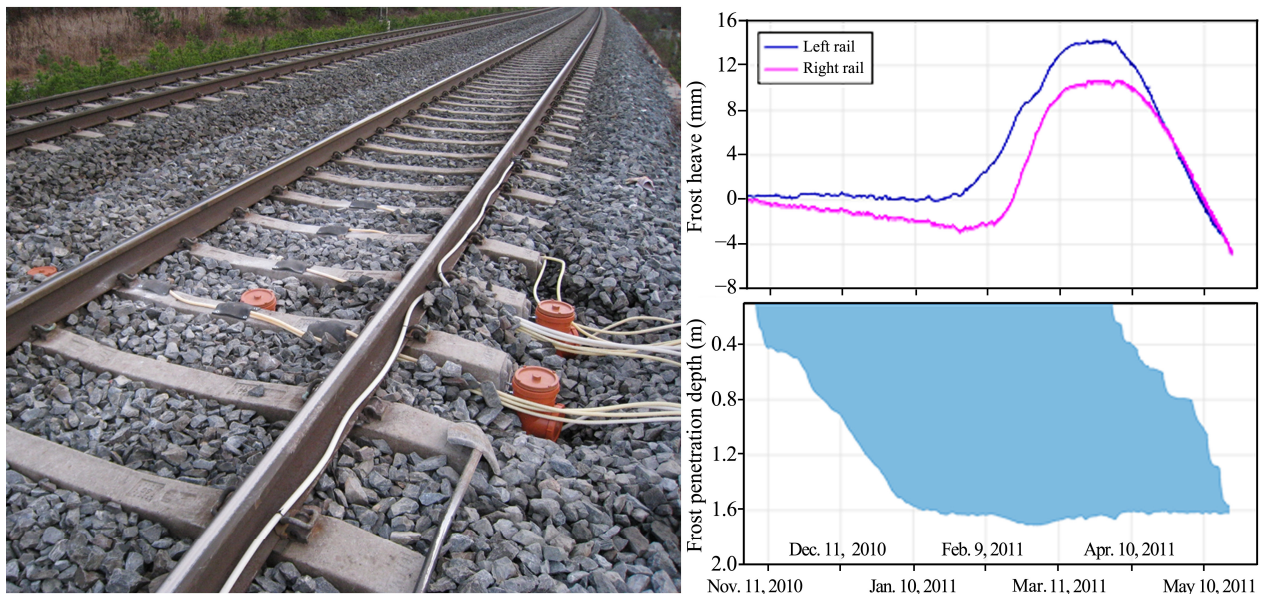


Figure 3 Field monitoring arrangement and format of monitoring results

Based on research findings, problems associated with frost action on the existing track network, which has been built before current quality standards, can be caused mainly by three factors: (1) thickness of non-frost-susceptible layers (ballast & subballast) is not sufficient to prevent the freezing of frost-susceptible subsoil, (2) subballast has been built of frost-susceptible material or (3) ballast has become highly fouled and consequently frost-susceptible. In addition, problems can be caused by discontinuities in frost protection such as transitions from cuttings to embankments, culverts, level crossings and switches. It was found that degradation (fouling) of ballast may turn the ballast material to frost susceptible (Nurmikolu and Kolisoja, 2008; Nurmikolu, 2010). Also, the subballast material, which, for example, may have been visually judged in the early 20th century as non-frost-susceptible, may still actually be frost-susceptible (Pykkänen and Nurmikolu, 2011).

4 Effects of frost action on Finnish railways

Finnish rail network is characteristically a mixed-traffic network serving both freight and passenger traffic. Most railway lines consist of just a single track. The maximum speed for passenger trains is 220 km/h, but 200 km/h is more common in the trunk network. On railway lines with these maximum speeds immediate action limit for deviations from longitudinal (vertical) level is only 7 mm, as determined with 5 m chord length.

The winters of 2009–2010 and 2010–2011 were very problematic. Frost action created the need for wintertime speed reductions on 827 km (winter of 2011) and 1,068 km (winter of 2010) of the 5,919-km track network in Finland. However, even though these winters were cold compared to previous ones, they were not extremely cold, as the air-freezing indices varied from those occurring statistically once in two years to those occurring once in eight years. During the preceding seven

winters (2003–2009), the average track length with temporarily reduced speed was only about 5 percent of the level that took place in the winters of 2010 and 2011. In addition to these temporary lower speed limits, frost action also substantially increased the need for regular track maintenance during these winter periods. Even though it is obvious that air-freezing index plays a determining role in frost action related problems, other climate aspects, such as snow depth, length of freezing period and depth of ground water table affect the severity of problems.

5 Integration of GPR and Track geometry data: a key for successful rehabilitation planning

Track geometry measurements are typically performed 4–6 times a year and provide important information for localization and classification of problems realized at the rail level. Steadiness of smooth track geometry is a primary indicator of track performance, but analyses on standard deviation of track geometry parameters over sequential measurements can provide relevant information also about the condition of structural components of track and causes of geometry problems. The comparison of measured data from various seasons can be a key to identification of problem sources, especially as done together with prevailing climate data that reflects the state of soil freezing and moisture during the measurement (Silvast *et al.*, 2013). Analysis presented in Figure 4 reveals season-related problems in longitudinal level (vertical deviation) from permanent, season-independent geometry problems.

The information on properties of structural layers and subsoil is a prerequisite for successful rehabilitation design of track geometry errors, including those caused by frost action. Long-term development work of ground penetrating radar data analysis has led to the current state, where GPR is a powerful tool not only for

determination of ballast and subballast thickness, but also for assessment of quality of the material. Also, fouling indices (Silvast *et al.*, 2010), moisture profile and frost heave susceptibility (Silvast *et al.*, 2012) of the materials can be analyzed. Integrated analysis of track geometry data of several years and seasons,

GPR data on structure thickness and quality, climate data from the same years as track geometry measurements, maintenance history database and asset database of the structures enables economical NDT-based identification of root causes of track geometry problems (Figure 5) (Silvast *et al.*, 2013).

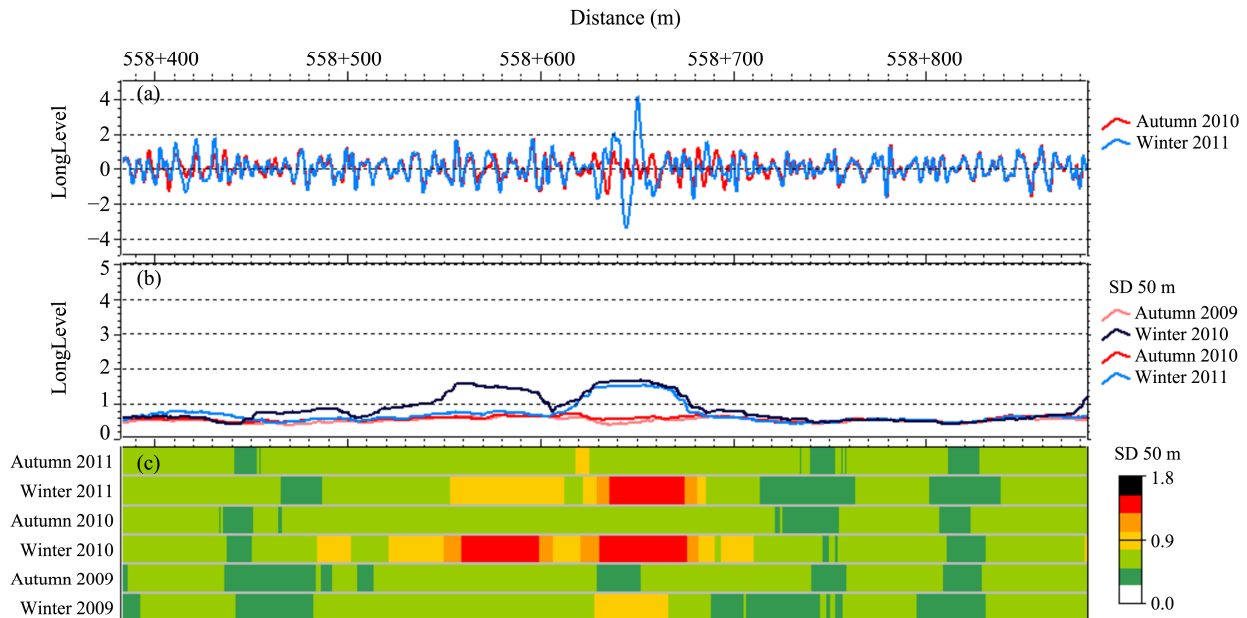


Figure 4 (a) Longitudinal level (track geometry) data from two sequential measurements, (b) standard deviation of 50-meter running window from four consecutive measurements and (c) as color-coded time series from six chronological measurements

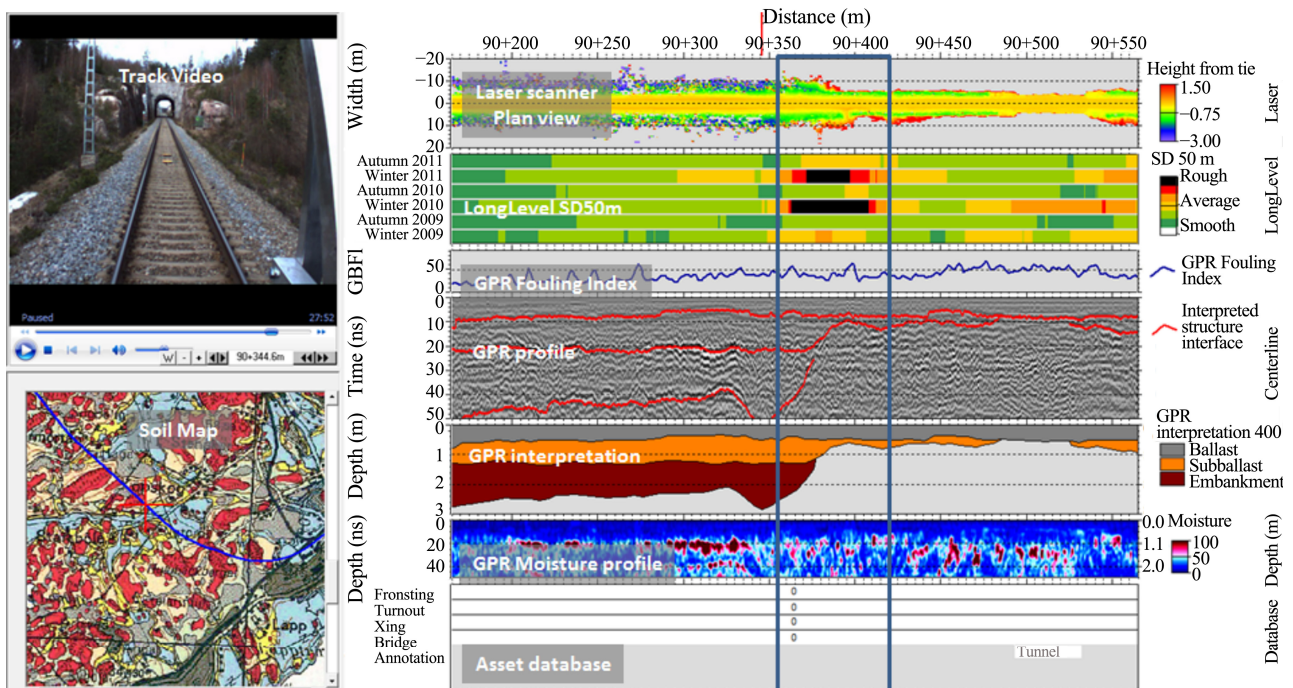


Figure 5 Integrated data analysis view from Railway Doctor®-software showing a seasonal problem due to frost heave and enabling the assessment of the causes of the problem

6 Rehabilitation methods

In wintertime, when the substructure is frozen, possible actions to maintain track geometry are very limited, as tamping is not possible. In order to avoid the restrictions on operation speed, special adjustment plates (pads) between rail and sleeper, depending on fastening system, are installed to level an isolated bump out on longer distance of track. However, as the heave situation changes with time, continual adjustment of the height and extent of the pads is very labor-consuming.

In order to permanently fix the frost action problem after substructure has melted, the identification of root causes of the problem is a prerequisite for choosing the right actions. If the reason can, for example through GPR-based ballast fouling index, be associated with frost-heave susceptible ballast, then ballast cleaning should be done. It has been proven that ballast is often blamed even though the actual problem is deeper in the structure. When the problem is identified to frost-susceptible subballast, severity of problems can be reduced by improving drainage. In cases of highly frost susceptible, subballast excavation and the replacement of subballast material is needed. Insufficient thickness of non-frost-susceptible ballast and subballast materials on top of frost-susceptible subsoil and subsequent freezing of subsoil is the most common problem. In that case, as an alternative for deep excavation work, frost insulation boards have been employed in Finland with good success for decades. It is efficient to install insulation boards directly below ballast during ballast cleaning (Figure 6). High quality extruded polystyrene (XPS) boards with minimum water intake tendency and compressive strength higher than 500 kPa are required, and their long-term performance is found to be good with life-cycle expectation of 40 years (Nurmikolu and Kolisoja, 2005).



Figure 6 Installation of XPS frost insulation boards during ballast cleaning

7 Conclusions

Especially on high-speed lines frost action is an enormous challenge for maintenance of track geometry. Frost action can be caused by ballast, subballast or subsoil. In order to choose an efficient repairing method on existing lines it is essential to identify the root cause of frost action. This can be done with the help of systematic in-depth integrated analysis of track geometry and high-quality GPR data. High quality XPS frost insulation boards have shown to be in many cases a life-cycle-economic alternative to deep excavation.

Acknowledgments:

The authors are thankful to Finnish Transport Agency for enabling the research.

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