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Effect of climate change on frost penetration depth in the subgrade soil beneath railway tracks: case study

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ABSTRACT
Frost heave along Canadian railways is a common issue that can result in track geometry issues and reductions in train speeds and rail traffic capacity. This study was conducted at a location prone to frost heave on VIA Rail Canada's Smith Falls subdivision to determine the maximum frost penetration depth at this site during the last 20 years and explore a correlation between frost depth and weather conditions for future anticipation of frost depth. The results include frost depth fluctuations over the last 20 winters using a thermal analysis conducted by TEMP/W, a regression between weather data and frost penetration depth, and predicted frost depth for the next 75 years based on a high greenhouse gas climate model. The results showed that frost depths estimated using conventional methods and numerical analysis were significantly different and the maximum frost depth tends to decrease in the future but it will be within the frost susceptible layers and could still be problematic at this site. So further monitoring or actions might be needed to prevent frost heave and consequent thaw softening at this location.

1 INTRODUCTION

Frost heave and thaw weakening are two states that result in negative effects of frost action in cold regions such as northern China, Russia, the USA, and Canada (Roghani and Hendry 2016, 2017; Roghani et al. 2015, 2017). Consequential frost heave has been observed in railway embankments along old or recently constructed railways in these areas, limiting train speeds in winter seasons. In theory, frost heave mostly occurs in finer materials or fouled ballast; however, monitored displacements indicate it can also occur in coarse fills considered to be non-frost susceptible materials (Li et al. 2016).

For development of ice lenses and frost heaving to occur, three factors must be present: freezing temperatures, a source of water, and a frost-susceptible soil. The most accepted definition of frost susceptibility is from the Highway Research Board Committee on Frost Heave and Frost Action in Soil (1955) and ISSMFE (1989), wherein frost-susceptible soils are those "*in which significant ice segregation will occur when the requisite moisture and freezing conditions are present*" (Nurmikolu 2010). The frost susceptibility of a material is highly dependent on the content and quality of the fines fraction (Nurmikolu and Kolisoja 2008; Nurmikolu 2010; Nurmikolu and Silvast 2013; Hendry et al. 2016) while the freezing temperature and source of water are site characteristics. Frost depth (or the depth to which soils may freeze and ice lenses develop) can significantly influence the destructive effects of frost heave and thaw softening, and the intensity of these two phenomena depends to a considerable extent on temperature and precipitation conditions. Therefore, it is crucial to develop a greater understanding of the frost depth and the meaningful effect of any atmospheric weather characteristics.

The present study is part of an extensive project at a section of track in Ontario, Canada that suffers from frost issues. This project aims to monitor the development of frost heave using instrumentation including ShapeArrays, strain gauges, borehole extensometers, thermistors, and piezometers (Roghani et al. 2019). In the first phase of the project, the frost susceptibility of the subgrade soil was investigated using samples from different layers (Roustaei et al. 2019). The experimental results showed medium to very high frost susceptibility classification for the soil layers at this site (Table 1). In addition, the water table was within 3 m (10 ft) of the track surface and thus provides the water source necessary for frost heave (FHWA NHI-05-037 2006). Moreover, the development of a numerical model based on *in situ* data collected during this phase resulted in illustration of the effect of various weather conditions, such as snow cover, on the frost penetration depth at this site. Having the results of the first phase in mind and considering the importance of frost penetration depth as the third factor necessary for the development of frost heave, this second phase of the study aimed to determine the maximum frost penetration depth at this site for the last 20 years and explore a correlation between frost depth and weather conditions for future anticipation of frost depth in this location.

1.1 Frost Depth Calculation

For several decades, frost depth determination and prediction have attracted researchers from academia and industry. Most frost heaving in some parts of Canada seems to occur in the latter half of the winter season, probably when the frost line has reached its maximum penetration (Armstrong and Csathy 1963). As such, predicting the depth to which soils may freeze and thaw can be helpful for guiding engineering designs. Several formulas as well as analytical and semiempirical models—such as Stefan, modified Berggren, and Chisholm and Phang—have been developed to predict the depth of frost penetration. The Stefan equation is derived from the fundamental equations of heat flow and storage (Eqs. 1 and 2; Yoder and Witczak 1975):

$$D = \sqrt{\frac{48kF}{L}}, \qquad [1]$$

where D is the depth of frost penetration (ft), k is the thermal conductivity (Btu/ft °F h), F is the freezing index (°F d), and L is volumetric heat of latent fusion (Btu/ft^3); and

$$L = 10434\ \omega\gamma, \qquad [2]$$

where ω is the moisture content and γ is the dry density (lb/ft^3). Among meteorological factors such as air temperature, sunshine, precipitation, and wind velocity, air temperature is probably the most significant. The use of 'degree-days of freezing' as a guide for calculating frost depth for a given area illustrates the strong influence of air temperature on soil temperature (Penner 1962).

In addition, the freezing index (also called 'coldness sun' by the U.S. Army Corps of Engineers) is the number of Fahrenheit degree-days above and below 32 °F between the highest and lowest points on the cumulative degree-days time curve for one freezing season. Local maps also exist from which the freezing index or even the frost penetration depth can be directly extracted for different regions of Canada. For example, Figure 1 is a map of southern Ontario published by the Ontario Ministry of Transportation as one of the Ontario Provincial Standards for Roads & Public Works. Although using this map provides a quick estimate of frost depth, which at this site is around 1.6 m, actual field data provide the most accurate information.

Numerical or analytical modeling techniques can also be used to estimate frost depth; however, the required input data are typically unavailable or expensive to collect (Luo 2014). Farrington et al. (2001) presented a frost penetration prediction model using numerical simulation, statistical regression, spatial interpolation, and GIS. Using their methods, they concluded seasonal maximum frost penetration depth can be reliably estimated by its relationship to the actual annual freezing degree index (AFDI), as long as a pavement-specific relationship is derived using meteorological data that account for region-specific weather dynamics. A regression of maximum seasonal frost penetration depth (derived from dynamic simulations of temperature and moisture flux in a pavement structure using actual climatic data) on AFDI showed a strong positive correlation and was useful for fitting a linear equation to the median and 90% upper prediction limit of maximum frost penetration depth.

NOTES:

A These values are approximate and should only be used where the recommendations of a geotechnical engineer are not available.

B This information is based on the Ministry of Transportation and Communications Research Publication RR225 "Aspects of Prolonged Exposure of Pavements to Sub-Zero Temperatures" dated December 1981.

C Values between contours should be interpolated. If interpolation is not possible, use the adjacent contour with the greater depth.

D Frost penetration depths are in metres.

Figure 1. Frost depth map for southern Ontario (Ontario Ministry of Transportation, 2010)

Soliman et al. (2008) introduced a simplified model to predict the frost penetration in Manitoba by developing a relationship with an acceptable accuracy between the depth of frost penetration and the freezing index by minimizing the effect of the other variables. Lee et al. (2013) provided a frost indicator with a methylene blue solution method to measure the frost depth (Luo 2014).

Because the actual frost depth is affected by material type, soil thermal properties, and soil water content as well as climatic conditions such as temperature, wind speed, precipitation, and solar radiation, this study concentrated on finding a simple correlation between air temperature, total snowfall, and frost penetration depth using a numerical model based on the soil properties and climate conditions at this specific site.

1.2 Climate Models

Air temperature and total snowfall are two of the most important requirements for frost depth prediction. Nowadays, various climate models forecast future weather conditions by considering climate change. The Earth's climate, past and future, is not static; it changes in response to both natural and anthropogenic drivers. Human emissions of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases (GHGs) now overwhelm the influence of natural drivers on the external forcing of the Earth's climate. Over the past 15 to 20 years, the growth rate of atmospheric carbon emissions from human activities has increased from 1.5 to 2 parts per million (ppm) per year due to increasing carbon emissions from human activities, in large part due to growing contributions from developing economies. Beyond the next few decades, the magnitude of future climate change will primarily be a function of future carbon emissions and the response of the climate system to those emissions. Climate projections are typically presented for a range of plausible pathways, scenarios, or targets that capture the relationships between human choices, emissions, concentrations, and temperature change (Hayhoe 2017).

The Representative Concentration Pathways (RCPs) form a set of GHG concentration and emissions pathways designed to support research on the impacts and potential policy responses to climate change (Moss et al. 2010; Van Vuuren et al. 2011). RCP 8.5 corresponds to a high GHG emissions pathway compared to the scenario literature (Fisher et al. 2007; IPCC 2008; Riahi et al. 2011). In this study, RCP 8.5 was used to predict frost depth prediction based on weather conditions for the next 75 years.

2 METHODS AND MATERIALS

2.1 Site Details

The study site is located at a section of VIA Rail's track in eastern Ontario. This subdivision is only used for passenger trains, and consists of 57 kg/m (115 lb/yd) continuously welded rail on ballasted track and wooden ties. It is classified as a class 5 track, which is Transport Canada's highest classification (Transport Canada's Rules Respecting Track Safety, 2011), and carries 160 km/h trains. The ballast layer and the gravel subballast, both 0.3-m thick, are underlain by old ballast material. Figure 2 shows the different layers of the subgrade with brief descriptions and Table 1 illustrates the frost susceptibility degrees extracted from experimental investigations (Roustaei et al. 2019). Figure 2 also shows the location of instrument installations at this site, including 20 thermistors located below the track surface in different layers and used in this study to monitor changes in temperature of the soil. These thermistors (model 3810, Geokon) are routinely used in permafrost applications to monitor underground soil and water temperatures. These sensors work in a temperature range from −20 to 80 °C with a resolution of 0.1 °C and accuracy of ±0.2 °C. The water table at this site is also within 3 m (10 ft) of the track surface and thus provides the water source necessary for frost heave. So, a frost-susceptible soil and source of water as two main factors for the development of frost heave are present at this site, and the frost depth as the third factor should be further investigated.

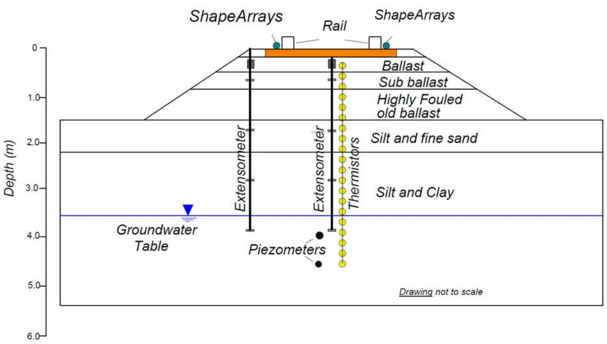

Figure 2. Schematic view of railway embankment and installed instrumentation

A numerical model was first developed to represent the thermal regime of the embankment and the underlying ground at the site using as inputs the data recorded for ambient temperature and from the deepest installed thermistor; it was then calibrated with the data recorded from the other thermistors for the previous winter. To determine the maximum frost penetration depth at this site and explore the correlation between frost depth and weather conditions for future anticipation of frost depth, multiple simulations were conducted based on weather data for the last 20 years (1999-2019) from the Kemptville and Appleton stations (weather stations closest to the site).

Table 1. Degree of frost susceptibility and types of soil samples

Depth (m)	Description	Degree of frost susceptibility
0-0.3	Crushed rock ballast-fouled	-
0.3-0.6	Gravel-grey, uniformly graded, trace of ice	-
0.6-1.2	Highly fouled ballast-the track appears to have been lifted over time and this layer is the ballast from before	Medium
1.2-1.5	Silt-trace fine sand, mostly silt, low plasticity, wet, dark grey	Very High
1.5-1.8	Fine sand and silt-medium plasticity, grey to dark, moist	Very High
1.8-4.2	Clay-trace silt, mostly clay, medium plasticity, moist, dark greenish grey	Very High

2.2 Numerical Model

Modeling was conducted using TEMP/W, a finite element software product for modeling thermal changes in the ground due to environmental changes or due to the construction of facilities, such as buildings or pipelines. TEMP/W requires that functions be specified for thermal conductivity and unfrozen water contents. These functions are dependent on temperature, which means they are only valid for a constant water content soil state, i.e., the water may turn to ice but the overall amount of water/ice is fixed throughout the analysis. All thermal characteristics of the soil layers shown in Figure 3 were estimated with respect to the type of soil (Table 2) and the TEMP/W manual in phase one of the study, with the model calibrated with temperature data recorded by the thermistors (Roustaei et al. 2019).

The water content of the subgrade layer samples was not available, so the volumetric water content parameter was determined by calibrating the model with the temperature data recorded by the thermistors. Other thermal properties were estimated with respect to the type of soil and the TEMP/W manual. A coupled soil-atmosphere process was used to investigate the effects of climate conditions in terms of snow on the temperature regime of soil layers. Surface Energy Balance (SEB) boundary conditions were considered one of the best solutions for modeling this process in the transient analysis (GEOSLOPE 2010).

In TEMP/W, the user is required to enter the air temperature, wind speed, snow depth, and albedo, all versus time, in addition to the latitude of the site for estimation of solar radiation. Of particular note here is the albedo, which will be influenced by snow cover characteristics, solar zenith angle, and cloud conditions. Snow surface albedo ranges from less than 0.60 for wet and melting snow to greater than 0.85 for fresh snow, can be greater than 0.90 under cloudy sky conditions, and is approximately 0.23 for green vegetation (Wendler and Kelley 1988; Zhang et al. 1996). A high snow surface albedo leads to a reduction in the absorbed solar energy and lowering of the temperature of the snow surface (Zhang 2005).

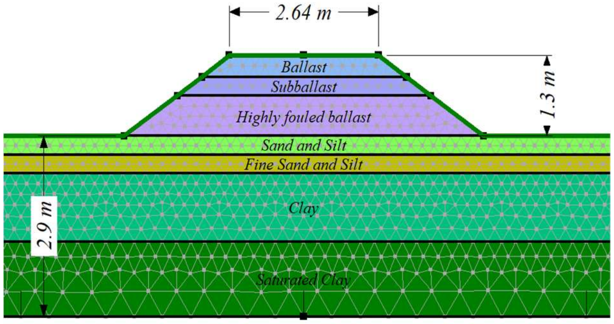

Figure 3. Geometry of the TEMP/W model

3 RESULTS AND DISCUSSION

3.1 Frost Penetration Depth

Frost penetration depth as the depth to which the groundwater in soil and consequently the soil medium are expected to freeze, is one of the main factors for the development of frost heave. It can be affected by different parameters, including ambient temperature, thermal conductivity of soil layers, snow or asphalt cover, and any nearby heat source. The exact depth of the frost line was determined from different thermal conditions.

Table 2. Properties of materials used in the TEMP/W model

Soil layer	Thermal conductivity (kJ/s/m/°C)		Volumetric heat capacity (kJ/m^3/°C)	*In situ* volumetric water content
	Frozen	Unfrozen		
Ballast	0.00056	0.00055	1800	0.18
Subballast	0.00085	0.0008	1800	0.18
Highly fouled ballast	0.0014	0.0012	1800	0.18
Sand and silt	0.0021	0.0017	2000	0.22
Fine sand	0.0024	0.0019	2000	0.25
Clay	0.0015	0.0013	2000	0.3
Saturated clay	0.00262	0.0013	2000	0.6

The TEMP/W model was calibrated with *in situ* recorded temperature data (2018-2019) in the first phase of this project. The results showed the ground thermal regime was primarily controlled by conductive heat transfer through the snowpack; increased conductivity due to compaction of the snow cover lessened this effect. Thicker snow cover maintained higher mean annual ground temperatures and shallower frost penetration (Roustaei et al. 2019). For a more comprehensive investigation of the effect of different amounts of snowpack as well as ambient temperature on the frost penetration depth, weather data for the last 20 years were used in the current part of the study. Figure 4 shows the ambient temperatures and snow cover depths during these winters, which were used as two of the main important inputs of the model, as well as the outputs in terms of frost penetration depths.

The frost line gradually climbs to its maximum depth starting from the first days of winter through to April, after which it remained deep even when the weather warmed up at the end of April. Although the ambient temperature went up and the weather became warmer, a limited area in the ground remained frozen in early spring and needed more time to thaw (Roustaei et al. 2019). Considering the characteristics of soil layers at this site as well as the ground profile, the frozen area developed in the very fine silty sand layer that has a very high degree of frost susceptibility and thus could result in the development of frost heave.

Additionally, thawing of the upper layers could create free water that is unable to drain through the impermeable frozen zone. This can flow to the freezing front of this zone and feed the growth of ice lenses. This phenomenon corresponds to a saturated substructure due to thaw softening (Li et al. 2016) and can cause extreme strength reduction in thawed soil layers due to the loss of effective stress. The two widest frost zones for the 20 different winters considered are shown in Figure 5, where the temperature of the blue area is below zero while the ambient temperatures are 18.3 and 10.3 °C on April 15 of 2003 and 2015, respectively. These frost zones last until mid-May and do not let moisture from the upper layers fully drain, which results in a thaw softening phenomenon.

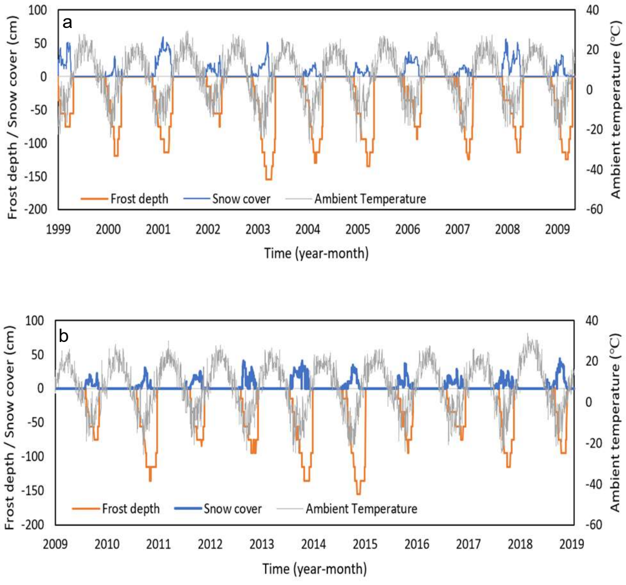

Figure 4. Ambient temperatures vs. snow cover and extracted frost depths from simulation for a) 1999-2009; b) 2010-2019

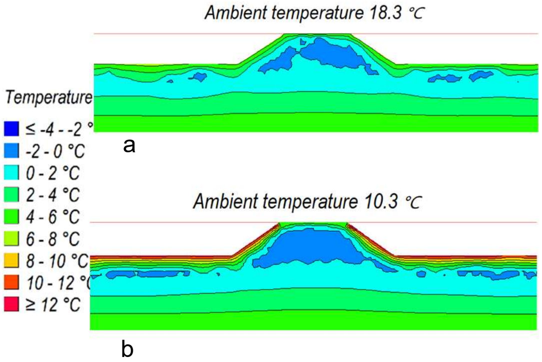

Figure 5. The two widest frost zones determined for the last 20 years: a) 2003-04-15; b) 2015-04-15

3.2 Linear Regression

A linear regression is usually used to find linear relationships between a target variable and one or more predictors. Technically, a regression analysis model is based on the sum of squares, which is a mathematical method to find the dispersion of data points. The goal of a linear regression model is to achieve the smallest possible sum of squares and draw a line that comes closest to the data. To build a regression model for predicting frost depth, frost depth becomes the response variable and two approaches can be taken. The first is to build a model to predict soil temperature at each depth, and then use linear interpolation to calculate frost depth from the predicted soil temperature values at each depth. The second, which is used in this study, first calculates soil frost depth values as the response variable and then builds the regression model directly to predict frost depth (Luo 2014).

In the first step, the calculated maximum frost depths from the numerical analysis during the previous 20 winters (1999-2019) were regressed against annual freezing degree days (FDDs) and the total annual snowfall using least squares multiple linear regression analysis. Results from this first model are summarized in Table 3 (centre column ‘first’ model), including an R-squared value indicating an acceptable general fit of our model with real observations and low P values showing meaningful additions of predictors to our model. In addition, the residual plots of our independent variables—annual snowfall and FDD—are randomly dispersed around the horizontal axis and demonstrate the linear regression model is appropriate for the available data (Figure 6a and 6b).

Figure 7 plots the estimated frost penetration depths from the adopted linear regression model for the last 20 years as well as those extracted from the numerical model, with the results showing good consistency between these two types of data. Due to these promising results, the regression equation was then used to predict frost penetration depth, specific to this site and its soil characteristics, using the RCP 8.5 climate model for future years.

Table 3. Summary of multiple linear regression outputs of the two regression models

Regression model	First	Second
Multiple R	0.79	0.72
R-Squared	0.62	0.52
Adjusted R-Squared	0.58	0.49
Standard Error	15.27	16.55
P-value (Variable 1) Snowfall	0.0304	-
P-value (Variable 2) FDD	6.81E-05	0.000306

Notably, many climatic models are based on temperature data and total precipitation while the amount of total annual snowfall is not considered. Although using snowfall data will result in more reliable frost penetration predictions with the first regression model, a second regression model using only the FDD as an independent variable could also be sufficient for frost depth prediction at this site in future years (Table 3, right column ‘second’ model; Figure 6c).

The freezing degree days extracted from the climate model adopted for this study, RCP 8.5, were then used for frost depth prediction based on weather conditions for the next 75 years (Climate Atlas of Canada 2019).

The frost depth penetration threshold shown in Figure 8 illustrates that climate change, reflected in warmer winters and fewer FDDs, will result in shallower frost penetration depths at this site in the future. The maximum frost depth for the next 20 years will be around 100 cm, which is located in the highly fouled old ballast that contains 18% fine materials and has a medium degree of frost susceptibility at present (which could increase in the future due to further fouling). After 2040, the maximum frost depth tends to decrease and reaches 60-70 cm, which is within the border of the subballast and highly fouled ballast layer.

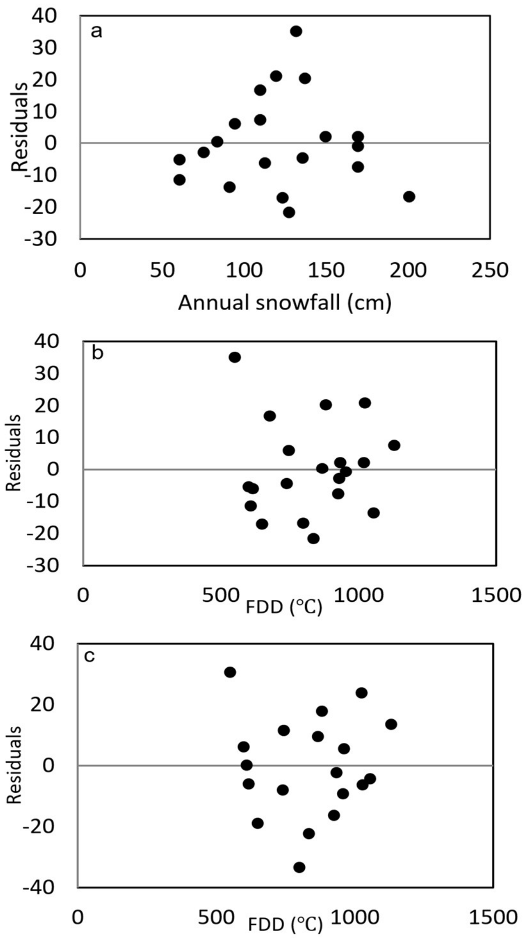

Figure 6. Residual plots of independent variables: a) annual snowfall in the first model; b) FDD in the first model; c) FDD in the second model.

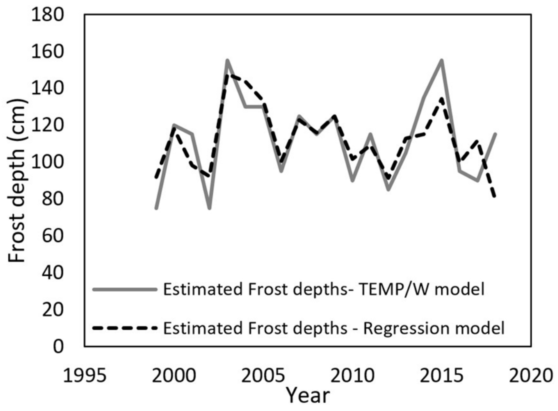

Figure 7. Estimated frost depth for the last 20 years

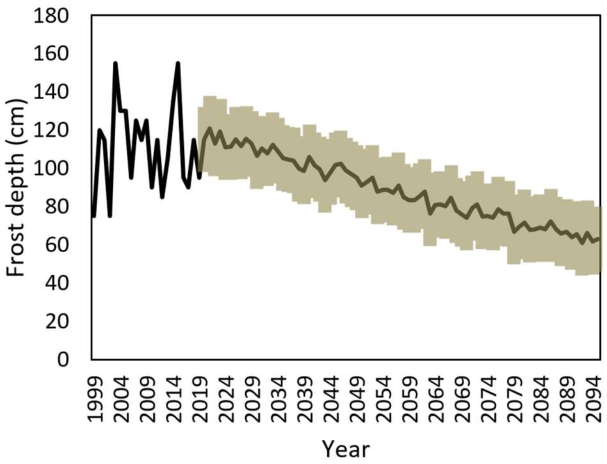

Figure 8. Predicted frost depth based on FDD data from the RCP 8.5 climate model for the next 75 years

4 CONCLUSION

Frost heaving of soils was originally thought to result from cold ambient weather, but present concepts indicate other factors influence the depth of freezing, such as the insulating effect of snow.

This study was undertaken to investigate the correlation of frost penetration depth with ambient temperature and snow cover and thus predict frost penetration depth in the future for a site located on VIA Rail Canada's Smith Falls subdivision.

The high frost susceptibility of soil layers at this site was demonstrated by experimental tests and a thermal model using TEMP/W previously calibrated using data from *in situ* installed thermistors. This model was used to analyze weather data for the last 20 years to determine the maximum frost penetration depth. Conventional maps show the frost penetration depth of this area at around 1.6 m, but the numerical model results for the last 20 years as well as *in situ* data from 2019 show the maximum frost depth at this location varies from 0.75 to 1.55 m and never exceeds this limit.

However, this depth still reaches frost susceptible layers of the subgrade and can result in frost heave. Moreover, a widespread frost zone developed in the embankment under the rail tracks and could last until May, and thus may be the main cause of thaw softening at this location. Two regression analysis models were also developed in this study based on the minimum sum of squares and maximum frost depth data for the last 20 years extracted from the numerical model. These models could be used for future forecasting of frost depth at this site.

Based on one of these regression models and the RCP 8.5 climate model, the maximum frost depth for the next 20 years was predicted to be around 100 cm, which is located in the highly fouled ballast that has a medium degree of frost susceptibility; however, this could change in the future with further fouling. After 2040, the maximum frost depth tends to decrease and reaches 60-70 cm, within the border of the subballast and highly fouled ballast layer. Therefore, frost heave could still be problematic at this site and further monitoring, or actions might be needed to prevent frost heave and consequent thaw softening at this location.

5 ACKNOWLEDGEMENT

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