

Frost susceptibility of subgrade soil beneath railway tracks: Case Study

Roustaei, M., Hendry, M. T.

Department of Civil and Environmental Engineering – University of Alberta, Edmonton, Alberta, Canada

Roghani, A.

National Research Council Canada, Ottawa, Ontario, Canada



ABSTRACT

Frost heave is a common issue for Canadian railway operators. Localized frost heave beneath the railway tracks can result in track geometry that may be hazardous to passing trains. A common method of ensuring the safe passage of trains is a reduction in train speed. These lower speeds cause delays and a reduction of capacity for rail traffic. This study monitored a location prone to the development of frost heave on VIA Rail track in Eastern Ontario.

This paper presents: (1) the instrumentation installed at the study site; (2) the characterization of the frost susceptibility of the soils; and, (3) a thermal analysis conducted using TEMP/W. The thermal analysis includes a new thermal boundary condition to evaluate the effect of the amount of snowfall on the temperature regime of the ground. The experimental results, the modelled and measured frost penetration depth, and the recorded frost heave showed a significant susceptibility of the site to frost action.

RÉSUMÉ

Le soulèvement dû au gel est un problème courant pour les exploitants ferroviaires canadiens. Les soulèvements dû au gel localisés sous les voies de chemin de fer peuvent créer une géométrie de la voie qui peut être dangereuse pour les trains qui passent. Une méthode courante pour assurer la sécurité du passage des trains consiste à réduire la vitesse des trains. Ces faibles vitesses entraînent des retards et une réduction de la capacité du réseau ferroviaire. Cette étude a permis de surveiller un site sujet au développement du soulèvement dû au gel sur la voie VIA Rail dans l'est de l'Ontario. Ce document présente: (1) l'instrumentation installée sur le site de l'étude; (2) la caractérisation de la sensibilité au gel des sols; et (3) une analyse thermique réalisée avec TEMP/W. L'analyse thermique inclut une nouvelle condition aux limites thermiques permettant d'évaluer l'effet de la quantité de neige sur le régime de température du sol. Les résultats expérimentaux, la profondeur de pénétration du gel modélisée et mesurée et le soulèvement enregistré dû au gel ont montré une sensibilité significative du site à l'action du gel.

1 INTRODUCTION

There is a long history in terms of the creation of railways and other infrastructure in China, Russia, the USA, and Canada in which frost heave and thaw weakening behavior of subgrade soils were fundamental considerations for designers and builders. From a design point of view, smoothness of the track surface is the main goal and therefore it is essential to control frost heave and associated phenomena in the track substructure that will deteriorate the track geometry (Li et al. 2016). For existing tracks, evaluating the frost susceptibility of subgrade soil layers is a priority. The problem of frost action damage is widespread and may be hazardous to passing trains or even cause reductions in train speeds and consequently in the capacity for rail traffic.

Frost heaving is expansion of the soil due to ice lens segregation; it is not formed by a simple phase change of pore water to ice but by inflowing pore water from unfrozen soil to segregating ice. The phenomenon may take place in materials such as soil, porous rock, and weathered mortar (Akagawa and Kodama 2005). Ice lenses will begin to form as the ground freezes from the top downward and water flows upward from capillary action. Capillary water will continue to feed the growth of the ice lens until the ground freezes below the ice lens and the capillary rise stops due to the impermeability of the frozen soil. New lenses can

continue to form, and layers of lenses can develop. Once the frost penetration stops, the lenses at the interface of frozen and unfrozen soil can grow quite large (Li et al. 2016). Moreover, thawing of ice lenses and frozen ground can create thaw softening, which is a worse problem than track heave. As the ice lenses melt from the top downward, excess free water is present, and this free water is typically unable to drain from the track due to the remaining frozen soil below that is relatively impermeable. The high water content that develops during thawing causes a softening of the soil and can result in a drastic reduction in strength due to loss of effective stress (Li et al. 2016).

Development of periodic ice lenses in seasonally cold climates is considered a well-known phenomenon. 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 Broad Committee on Frost Heave and Frost Action in soil (1955) and ISSMFE (1989) and states that "soil 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 (Nurmikolu and Kolisoja 2008, Nurmikolu 2010, Nurmikolu and Silvast 2013). Silt-sized fines and rock flour generated due to the abrasion and degradation of railway ballast may

be highly susceptible to frost heave (Nurmikolu and Kolisoja 2005, 2008, Hendry et al. 2016). The subballast material may also be frost-susceptible even though it may have been visually judged in the early 20th century as non-frost-susceptible (Pylkkänen and Nurmikolu 2011, Nurmikolu and Silvast 2013).

Laboratory work has been conducted to increase the understanding of frost heave. Chamberlain (1987) recommended that a laboratory frost heave test should measure both heave and thaw weakening, but most laboratory studies use the one-dimensional frost heave testing methodology adopted from Konrad (1999). Hendry et al. (2016) performed frost heave tests with modifications including the addition of a fluorescent tracer to monitor the freezing front on Devon silt and the fines generated from the abrasion of an aggregate. Their results show a contradictory assessment of frost heave susceptibility based on the rate of segregation heave and the segregation potential due to the transient conditions that result from the differing thermal conductivity of the soils. Another study on samples from ballast and subgrade layers of railway tracks in northern Japan by Akagawa et al. (2017) shows that frost heave susceptibility of the mixture is almost proportional to the saturation ratio of fine materials in its voids, even if the voids of the crushed rock are not saturated with fine materials. After all of the voids are filled, a segregating ice lens starts to push up the overburden, i.e., the ballast layer, and cause macroscopic upheaval due to frost heaving.

In addition to laboratory investigations, numerical methods have recently played an important role in understanding the freeze thaw phenomenon. Navikas and Sivilevičius (2017) model the temperature regimes of railway construction layers using SV HEAT software. Their results show snow cover acts as a thermal insulation layer. Railway construction with a snow cover had a lower freezing depth, and the temperature difference between layers with and without snow cover decreased with increasing distance from the top of the ballast layer. The thermal regime through the snowpack and the underlying ground were monitored at two study sites in Canada during the winter of 2014-2015 by Lanouette et al. (2015). They show the ground surface temperature reduction is more important in the first few centimeters of snow, then progressively diminishes as the snowpack gets thicker and denser.

The frost heave phenomenon is a great challenge for railway foundations on seasonally frozen ground and must be considered by railway corporations. This present study was undertaken at a section of VIA Rail's track in Eastern Ontario that has suffered from frost issues in the past (Roghani et al., 2019). The frost susceptibility of the subgrade soil was investigated using samples from different layers. These data were used to develop a numerical model to investigate the annual thermal regime of the subgrade and evaluate the effect of climate factors, such as snow cover, on the range of temperature conditions and frost penetration.

2 METHODS AND MATERIALS

2.1 Site details

The study site is located at a section of VIA Rail's track in eastern Ontario (Figure 1). This subdivision is only used for the passenger trains, and consists of 57 kg/m (115 lb/yd) continuously welded rail on ballasted track and wooden ties. This subdivision is classified as a class 5 track, which is the Transport Canada's highest classification, 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. This figure also shows the location of instrument installations at this site, including 20 thermistors located below the track surface in different layers to monitor changes in temperature of the soil layers. This study is part of an extensive project, the purpose of which is to monitor the development of frost heave using instrumentation including ShapeArrays, strain gages, borehole extensometer, and piezometers (Roghani et al. 2019).

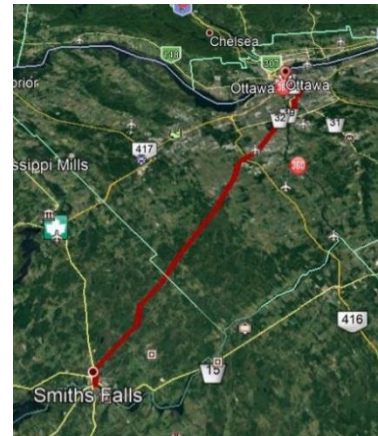


Fig. 1. VIA Rail Smith Falls subdivision located southwest of Ottawa

2.2 Site Characterization

Eight samples were collected from ballast and subgrade layers through two boreholes 1 and 4 (figure 2) and the frost susceptibility of four samples from Borehole 4, which were assumed to be close to the frost line were evaluated using wet sieve analysis and the standard test methods for Liquid Limit, Plastic Limit, and Plasticity Index of soils (ASTM D6913/D6913M 2017, ASTM D4318 2017); these methods provide information on the frost-susceptibility of a soil, which is highly dependent on the fines content and escalates with increasing fines percentage, decreasing activity of the fines fraction, and, for a specific fines fraction mineralogy, increases in the liquid limit of the fines fraction (Rieke et al., 1983). Table 1 shows the characteristics of the samples during collection and after laboratory tests as well as their degree of frost susceptibility as per the frost susceptibility classification of soils (NCHRP 1-37A 2002), which indicates the subgrade soils of railway track in this location have very high degrees of frost susceptibility.

The water table at this site is also within 3 m (10 ft) of the track surface and therefore could increase the probability of frost heave (FHWA NHI-05-037 2006). Furthermore, site observations indicate the aged ballast is highly fouled, has a significant amount of fines (18%), and therefore has a medium degree of frost susceptibility (Akagawa et al. 2017).

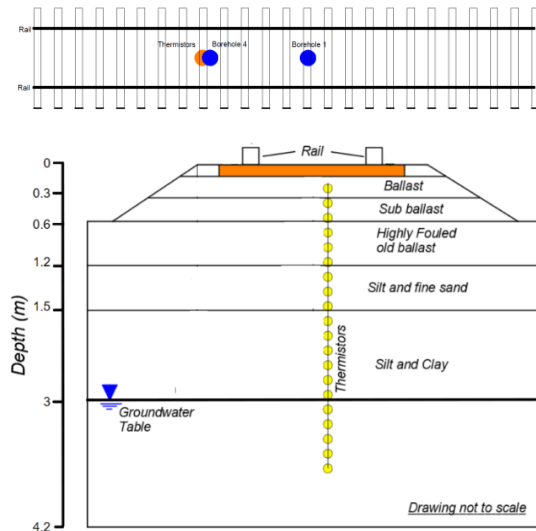


Fig. 2. Schematic view of railway embankment and installed instrumentation

2.3 Temperature Regime

Because freezing temperature is one of the essential factors for the occurrence of frost heaving, the temperature of the soil layers as well as the ambient temperature were recorded every 10 minutes by 20 thermistors (model 3810, GEOKON, Inc., USA) installed at 20-cm intervals below the track surface in different layers. Figure 3 shows the ambient temperature in addition to recorded temperatures from sensors S1, S5, S10, S15, and S20 located 0.35, 1.15, 2.15, 3.15, and 4.15 m below the track, respectively. The data in this figure show that the effects of fluctuations in ambient temperature as well as penetration of cold weather on soil temperature decline with depth in the subgrade layers. The freezing depth or the depth of frost line may move depending on the ambient temperature and for how long a period below-freezing temperatures persist.

2.4 Development of Numerical Model

The laboratory results and site investigations confirm the main factors for the development of ice lenses—frost susceptible soil, a water source, and freezing temperatures—are present at this site. A numerical model was developed to represent the thermal regime of the embankment and the underlying ground at the site using the recorded data from sensors as the inputs. The model was calibrated, and then different simulations conducted to quantify the impact of different boundary conditions, such as snow, on the thermal regime in the ground and

consequently explore the possible effect on the frost heave potential of the site.

Modelling was conducted using TEMP/W, a finite element software product for modelling thermal changes in the ground due to environmental changes or due to the construction of facilities, such as buildings or pipelines. While TEMP/W can be used with SEEP/W to model the effect of moving water on heat transfer, it cannot deal with the very complex and poorly understood physical coupling between water, ice, air, and soil during heaving (GEOSLOPE 2010). TEMP/W requires that functions be specified for thermal conductivity and unfrozen water contents. These functions are dependent on temperature, which means that they are only valid for a constant water content soil state. The water may turn to ice, but the overall amount of water/ice is fixed throughout the analysis.

No data were available for the water content of the subgrade layer samples, so the volumetric water content parameter was determined by calibrating the model with the temperature data recorded from the thermistors. Other thermal properties were estimated with respect to the type of the soil (Table 2). The geometry of the entire model was created based on the actual dimensions of the site. To minimize the boundary condition effect, the finite-element mesh was extended to a depth of 4.2 m and a lateral length of 30 m, as shown in Figure 4.

For the thermal analysis, boundary conditions were defined according to the type of analysis: *steady-state* or *transient*. A transient analysis used in this study by definition means one that is always changing and it considers how long the soil takes to respond to the user boundary conditions. In order to move forward in time during the transient analysis, the soil temperature conditions at the start of the time period should be defined as well as the thermal boundary conditions.

The recorded data from thermistors in one day have been used to provide initial conditions while their data from the other days of the year were essential for the calibration process of the numerical model.


The initial conditions for the transient analysis can have a significant effect on the solution; unrealistic initial conditions will lead to unrealistic solutions, which may be difficult to interpret, especially in the early stages of transient analysis (GEOSLOPE 2010).

After defining the initial temperatures, the recorded ambient temperature data from the site were applied to the model and the depth of snow cover extracted from the weather station near the site. The results of this analysis were calibrated using the thermistor recordings.

Defining thermal conditions on the boundaries of a thermal analysis is a key component in these types of analyses and are usually considered as “boundary-valued” problems. Obviously, for heat flow to occur, temperature differences between two points or lines are needed.

Herein, the first step in the transient analysis was to define boundary conditions of the ground surface as well as a designated line in the subgrade layers, which we took as the depth of the last installed thermistor (4.15 m). The temperatures of these two borders were defined according to data recorded from the site on May 9, 2018.

Table 1. Degree of susceptibility and types of soil samples regarding NCHRP 1-37A, 2002

Depth (m)	Sample Number	Groundwater	Description Soil Group Name: modifier, color, moisture, density/consistency, grain size, other descriptors Rock Description: modifier, color, hardness/degree of concentration, bedding and joint characteristics, solutions, void conditions.	Percentage finer than 0.075 mm	Plasticity Index	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	B44		Highly fouled ballast it seems that the track has been lifted over time and this layer is the ballast from before	18	-	Medium
1.2-1.5	B43		Silt trace fine sand, mostly silt, low plasticity, wet, dark grey	31	-	Very High
1.5-1.8	B42		Fine sand and silt medium plasticity, grey to dark, moist	21	-	Very High
1.8-4.2	B41		Clay trace silt, mostly clay, medium plasticity, moist, dark greenish grey	-	<12	Very High

3m

Figure 5 shows these data (logged each 10 min) and illustrates that the deepest thermistor (4.15 m) is a well-selected point for the analysis because the ambient temperature fluctuations have no effect at all on soil temperatures at this depth. The primary results of the numerical model shown a good consistency with the thermistor data and indicate the model is sufficiently accurate to be used for further analysis for the purposes of this study. Climate conditions in terms of precipitation or snow can significantly change the temperature regime of soil layers. This phenomenon can be generally considered a coupled soil-atmosphere process in which water transferring across the ground can influence the thermal energy flux as well as the ground surface temperature. Surface Energy Balance (SEB) boundary conditions are considered one of the best solutions for modeling this process in the transient analysis (GEOSLOPE 2010).

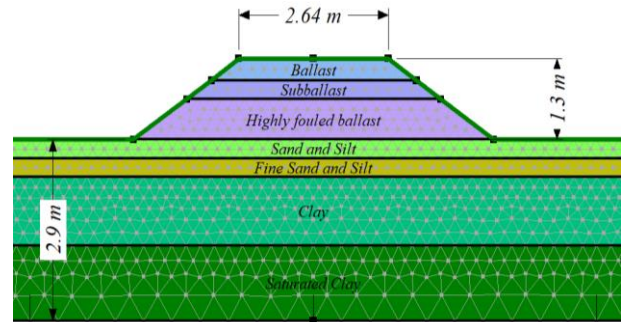


Fig. 4. Geometry of the TEMP/W model

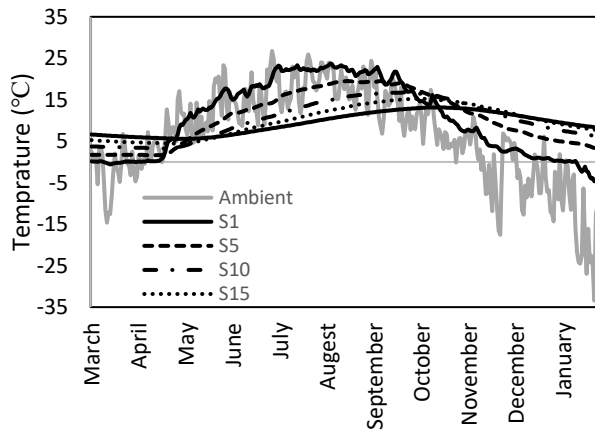


Fig. 3. Ambient and thermistor temperatures (March 2018-January 2019)

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

Soil layer	Frozen thermal conductivity (kJ/sec/m ² °C)	Unfrozen thermal conductivity (kJ/sec/m ² °C)	Volumetric heat capacity (kJ/m ³ °C)	In situ volumetric water content
Ballast	0.00062	0.0006	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	0.00162	0.0013	2000	0.6

The SEB boundary condition is calculated by solving the surface energy balance equation, which is based on definitions such as net solar (shortwave) radiation, net terrestrial (longwave) radiation, and sensible heat flux or latent heat flux. In TEMP/W, the user is required to enter the air temperature, wind speed, snow depth, and albedo, all versus time, in addition to latitude of the site for estimation of solar radiation. In this study the climate data of the closet weather station, Kemptville CS in Ontario, has been used. Of particular note here is 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 and can be greater than 0.90 under cloudy sky conditions, it could also be approximately 0.23 for green vegetation. (Wendler and Kelly 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). Figures 6 and 7 shows the data used in the transient analysis of this model.

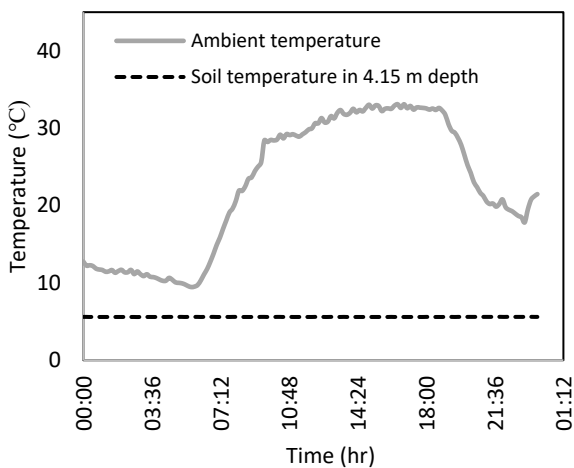


Fig. 5. Temperature data of ambient and soil used as thermal boundary conditions

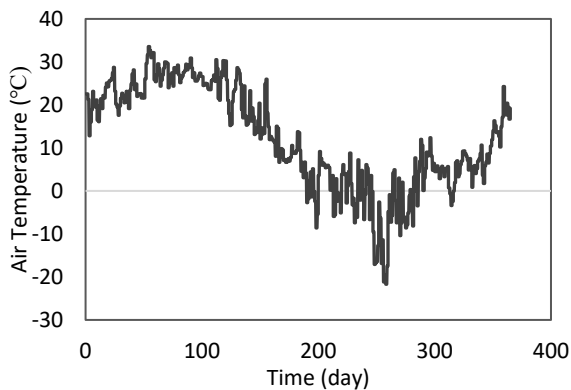


Fig. 6. Air temperature data used in the transient analysis for 365 days

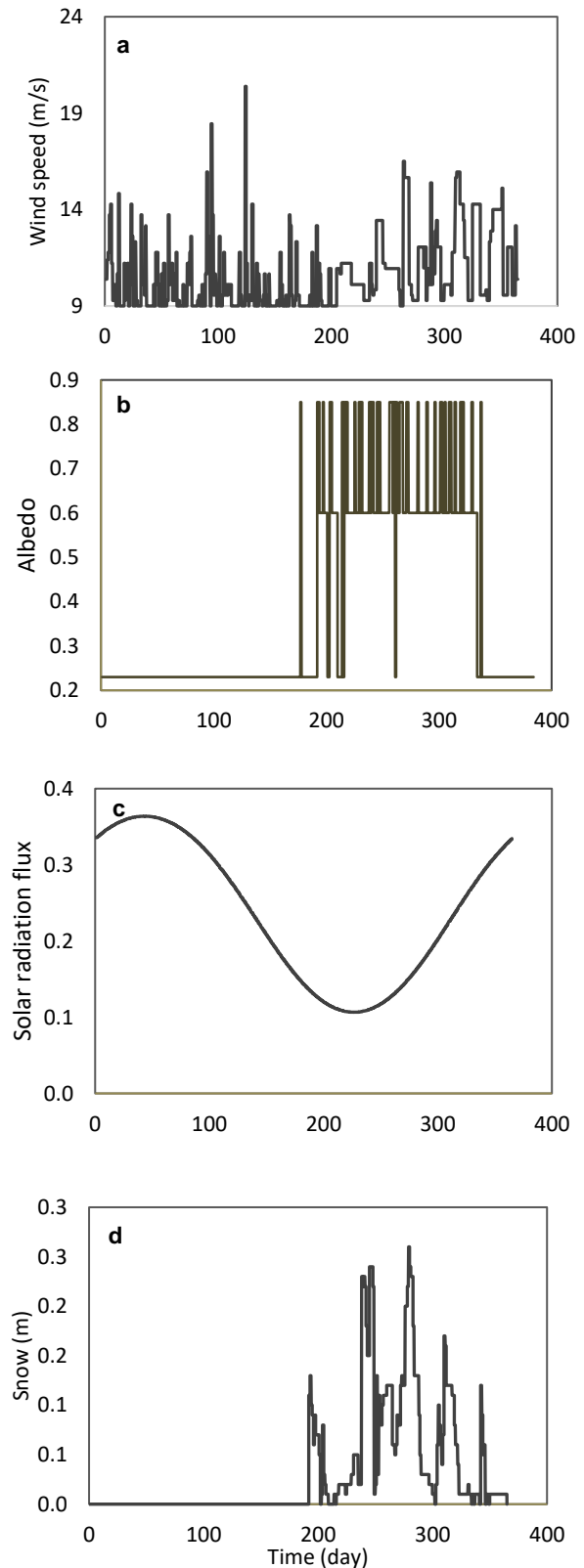


Fig. 7. a) Wind speed b) albedo c) solar radiation flux and d) snow cover data used in the transient analysis for 365 days

3 RESULTS AND DISCUSSION

3.1 Temperature variation

Variation of temperature between the bottom ($T_{surface}$) and the top (T_{air}) of the snowpack was used to determine a ground surface temperature corresponding to a certain snow thickness.

Figure 8 shows temperature variation ΔT ($T_{surface} - T_{air}$) versus the thickness of snow cover on the ground in winter extracted from the model. The increase of snow thickness has a notable impact on the variation of temperature. This is in contrast to previous investigations that illustrated more subtle effects of snow cover on the ground surface temperature over an optimal snow thickness of 40 cm (Zhang 2005, Lanouette et al. 2015). This figure also shows that the highest ΔT values tend to occur subsequent to large snow falls.

The Difference between Ground temperature and Air Temperature (DGAT) is another common indicator of the effect of snow cover, and can also be used to show the effect on the ground temperature. This parameter removes other influential factors and highlights the effect of snow cover on the underlying ground. Positive or negative DGAT values indicate a warming or cooling effect of the snow cover, respectively (Zhang et al. 1996). Figure 9 shows the DGAT for three different depths of ground in the model for an entire year as well as the amount of snow cover in winter. This figure illustrates that the difference between ground temperature and air temperature significantly increases with depth and that ground covered with snow results in warmer soil layers. The results in Figures 8 and 9 show that ground temperatures are higher for thicker snow cover. Snow cover has a low thermal conductivity and high albedo and emissivity, and therefore can cause a reduction in the absorbed solar energy and an increase in the outgoing long-wave radiation, which results in a cooler snow surface. This characteristic can insulate the ground, reducing the amount of cooling that occurs during the cold season (Zhang et al. 1996, Li et al. 2016). Moreover, snow

has a high latent heat of fusion, which makes snowmelt a heat sink. The overall impact of snow cover on the ground thermal regime depends on a number of factors, including timing, duration, accumulation, melting processes, density, structure, thickness, and interactions with micrometeorological conditions (Zhang 2005, Li et al. 2016). This phenomenon is therefore multifaceted, and the effect of other parameters such as ambient temperature in terms of colder winters should be thoroughly investigated.

3.2 Freezing n-factor (n_f)

Knowledge of the freezing n-factor (n_f) is also helpful for investigating the effect of snow cover on the temperature regime. This factor is usually defined as the ratio of the freezing degree-days or even the temperature of ground surface (under the snow cover) versus the same parameter for the ambient environment (above the snow). This study used the second definition and calculated the n-factor from the following equation:

$$n_f = \frac{T_{surface}}{T_{air}} \quad [1]$$

Fluctuations in the freezing n-factor extracted from the TEMP model and shown in figure 10 demonstrate that the first few centimeters of snow have more effect on the ground temperature and consequently the n-factor; as the snowpack becomes denser, the impact decreases. This reduction in the effect of snow cover on the results is due to microstructural changes in the snow cover. Such changes will result in an up to four-fold increase in the thermal conductivity of the snow cover when compacted, hence diminishing the insulating characteristics (GEOSLOPE 2010). It is worth mentioning that DGAT is a more efficient parameter in comparison to the freezing factor when the surface or air temperatures are around zero.

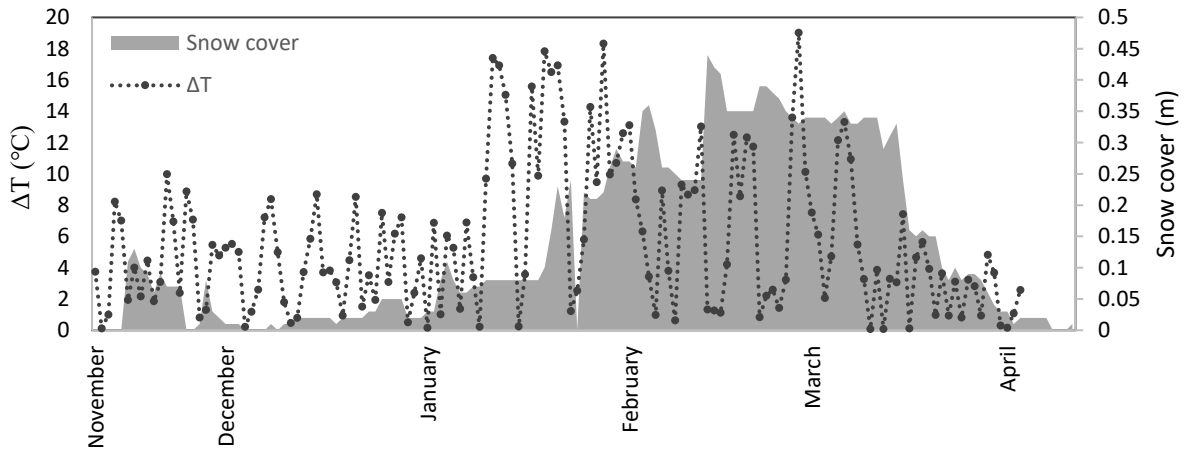


Fig. 8. Variation of temperature (ΔT) between the bottom and top of the snowpack in the model (November 2018 - April 2019)

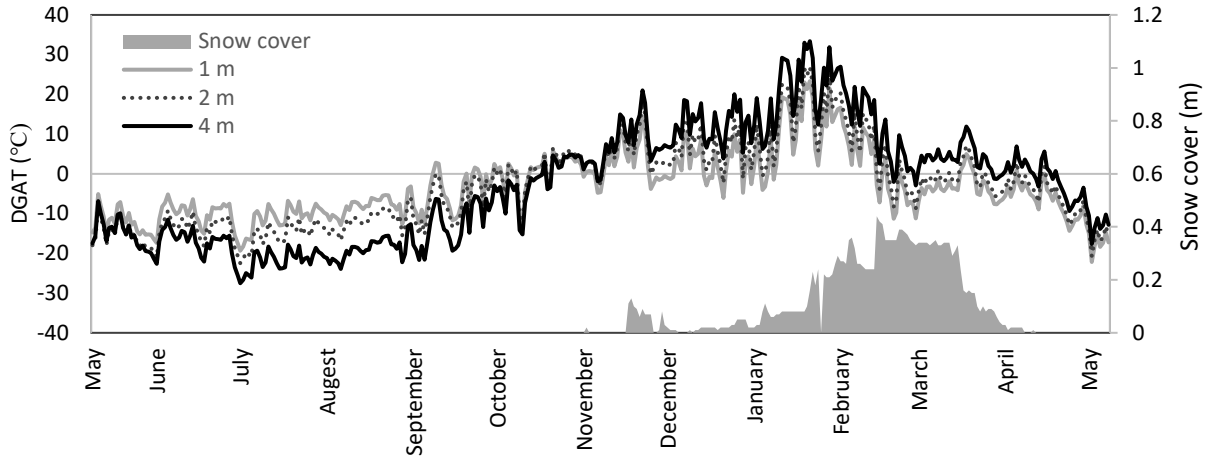


Fig. 9. Difference between Ground temperature and Air Temperature (DGAT) at depths of 1, 2, and 4 m below ground in the model during a year (May 2018-May 2019)

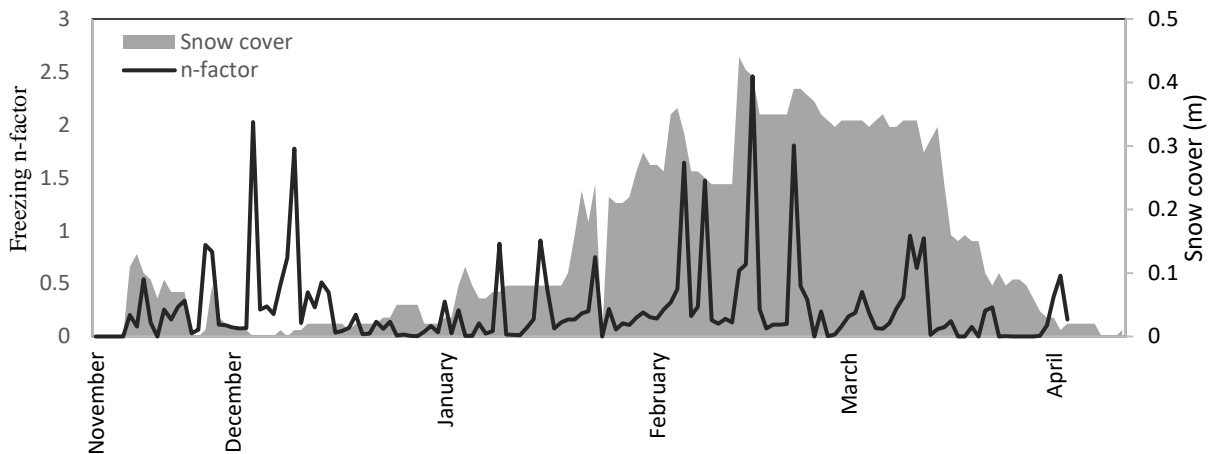


Fig. 10. Variation of freezing n-factor between the bottom and the top of the snowpack in the model (November 2018 - April 2019)

3.3 Frost penetration depth

Frost line or frost penetration depth is the depth to which the groundwater in soil and consequently the soil medium are expected to freeze. This depth is one of the main factors for development of frost heave and 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 during winter 2018-2019 was determined from TEMP/W model as well as *in situ* recorded temperature data and is shown in figure 11. This figure illustrates that the results from TEMP model have a good consistency with the *in situ* recorded data particularly in depth of frost penetration, but some differences are visible in the period of frost action between two graphs.

3.4 Frost heave

As previously mentioned, freezing temperatures, a source of water and a frost susceptible soil must be present for

development of ice lenses and frost heaving to occur. Frost susceptible soil layers of this site as well as water level around 3 meters depth and the frost penetration depth showed in the last section, could significantly increase the probability of frost heave at this site. During the last freezing season (Feb. 2019) a survey of this site showed a heave of 10- 18 mm at this location.

4 CONCLUSION

Ice lensing and consequent frost heaving develop when freezing temperatures occur in a frost susceptible soil with a source of water nearby. This study was undertaken to investigate the potential of frost heave in a subgrade soil beneath railway track at a site located in Eastern Ontario. The classification of soil layers of this site showed medium to very high frost susceptibility as well as a water table in depth of 3 m. The presence of freezing temperatures was modeled using TEMP/W software. This numerical model showed the effects of different boundary conditions on the ground thermal regime. The model results illustrated that thicker seasonal snow cover tends to result in relatively

higher mean annual ground temperatures. The ground thermal regime is primarily controlled by conductive heat transfer through the snowpack; increasing the conductivity due to the compaction of snow cover lessens this effect. Overall, numerical modeling, based on the monitoring data, indicates that this section of railway track should be considered as having a high susceptibility to frost heave in cold winters or those with less snowfall. The development of frost heave within the subballast and subgrade layers could have subsequent effects on track quality and performance. In the near future, the calibrated TEMP/W model with *in situ* recorded temperature data (2018-2019) will be used in order to investigate the effect of different amounts of snowpack as well as different ambient temperatures on the penetration depth of cold weather and the frost line of this site. The ultimate goal of this research program is to find out the correlations between the weather temperature, the amount of snow fall and frost penetration depth and investigate the effect of different climate scenarios on the amount of frost penetration depth might be feasible. Although this goal was not realized within this research, the results of this part could be a useful database for the next part.

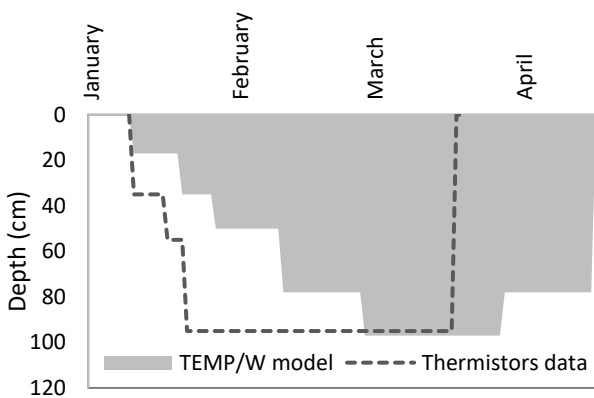


Fig. 11. Frost penetration depth of TEMP/W model and in situ data (January 2018-April 2019)

5 ACKNOWLEDGEMENT

The authors would like to acknowledge Infrastructure Canada for providing funding, VIA Rail Canada for providing access to its track, and RailTerm for facilitating the field work. The authors also would like to thank Jean-Marie Br  h   and Vincent Le Borgne from GKM. Special thanks to Paul Charbachi from VIA Rail Canada, Dr. Juan Hiedra Cobo, Dr. Jon Makar, and Marianne Armstrong from National Research Council Canada for supporting this project.

6 REFERENCES

Akagawa, S., Horib, M., Sugawarac, J. 2017. Frost heaving in ballast railway tracks. *Procedia Engineering*, 189: 547–553.
 Akagawa, S., and Kodama, N. 2005. Frost weathering in rocks and mortar, *40th U.S. Symp. Rock Mechanics, ARMA/USRMS 05-759, CD Distribution*, 1-9.
 ASTM Standard C325-07, 2014, Standard Guide for Wet Sieve Analysis of Ceramic Whiteware Clays, *West Conshohocken, PA*.

ASTM Standard D4318-17, 2017, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, *West Conshohocken, PA*.
 Chamberlain, E.J. 1987. A Freeze-Thaw Test to Determine the Frost Susceptibility of Soils, Special Report 87-1, U. S. Army Corps of Engineers, *Cold Regions Research and Engineering Laboratory*.
 FHWA NHI-05-037, 2006. Geotechnical Aspects of Pavements. *U.S. Department of Transportation, Federal Highway Administration*.
 GEOSLOPE 2010. Thermal Modeling with TEMP/W 2007, An Engineering Methodology, Fourth Edition, *GEOSLOPE International Ltd, Calgary, AB, Canada*.
 Hendry, M., Onwude, L., and Segoo, D. 2016. A laboratory investigation of the frost heave susceptibility of fine-grained soil generated from the abrasion of a diorite aggregate. *Cold Regions Science and Technology*, 123: 91–98.
 Highway Research Board Committee on Frost Heave and Frost Action in soil, 1995, *Highway research Broad Bulletin*. No. 111: 107-110.
 ISSMFE (International Society of Soil Mechanics and Foundation Engineering) Technical Committee on Frost, TC-8, 1989. Work Report 1985-1989. *VTT Symposium 94, Frost in geotechnical engineering, Saariselka, Finland*, 13-15.3.1989. Espoo, VTT. Vol 1: 15-70.
 Konrad, J. 1999. Frost susceptibility related to soil index properties. *Canadian Geotechnical Journal*, 36(3): 403–417.
 Lanouette, F., Fortier, G.D.D., and Lemieux, C. 2015. Influence of snow cover on the ground thermal regime along an embankment built on permafrost: In-situ measurements. *GeoQuebec 2015, Qu  bec City, Qu  bec, Canada*
 Li, D., Hyslip, J., Sussmann, T. and Chrismer, S. 2016. Railway Geotechnics. CRC Press, *Taylor & Francis Group, Boca Raton, FL*.
 Navikas, D., and Sivilevicius, H. 2017. Modelling of snow cover thickness influence on the railway construction temperature regime under variable weather conditions. *Procedia Engineering* 187: 124–134.
 NCHRP 1-37A, 2002. Design of New and Rehabilitated Pavement Structures, *National Cooperative Highway Research Program by ERES Division of ARA*.
 Nurmikolu, A. 2010. Fouling and frost susceptibility of railway ballast and subballast, Field and laboratory study, *VDM VERLAG DR. M  LLER, Germany*, ISBN 978-3-639-23623-1.
 Nurmikolu, A., and Kolisoja, P. 2005. Extruded polystyrene (XPS) foam frost insulation boards in railway structures. *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan*, September 12–16.
 Nurmikolu, A., and Kolisoja, P. 2008. The effect of fines content and quality on frost heave susceptibility of crushed rock aggregates used in railway track structure. *Proceedings of the 9th International Conf. on Permafrost*. Fairbanks, USA, June 29–July 3. Vol. 2, pp. 1299–1305.
 Nurmikolu, A., and Silvast, M. 2013. Causes, effects and control of seasonal frost action in railways. *Sciences in Cold and Arid Regions*, 5(4): 0363–0367.
 Pylkk  nen, K., and Nurmikolu, A. 2011. Frost susceptibility of railway subballast materials. *Proceedings of International Heavy Haul Association Conference, IHHA 2011, June 19–22, Calgary, Canada*.
 Rieke, R., Vinson, T.S., and Mageau, D.W. 1983. The role of specific surface area and related index properties in the frost heave susceptibility of soils. *Proceedings of the 4th International Conference on Permafrost*, Fairbanks, Alaska, pp. 1066–1071.
 Roghani, A., Hiedra Cobo, J., Charbachi, P. 2019. Studying the impact of freeze thaw cycles on performance of railway tracks. *Proceedings of International Heavy Haul Association Conference, IHHA 2019, June 12–14, Narvik, Norway*.
 Wendler, G., and Kelley, J. 1988. On the albedo of snow in Antarctica: A contribution to I.A.G.O. *Journal of Glaciology*, 34: 19–25.
 Zhang, T., Stamnes, K., and Bowling, S.A. 1996. Impact of clouds on surface radiative fluxes and snowmelt in the Arctic and Subarctic. *Journal of Climate*, 9: 2110–2123.
 Zhang, S., Sheng, D., Zhao, G., Niu, F., and He, Z. 2016. Analysis of frost heave mechanisms in a high-speed railway embankment. *Canadian Geotechnical Journal*, 53: 520–529
 Zhang, T. 2005. Influence of the seasonal snow cover on the ground thermal regime. *Reviews of Geophysics*, 43: RG400