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Modelling of Snow Cover Thickness Influence on the Railway Construction Temperature Regime under Variable Weather Conditions

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Abstract

This article presents results of the modelling of temperature regimes of railway construction layers in application of the SV HEAT software. In one case, ambient air temperature affects the railway construction in presence of a snow cover and in another case – without it. Temperature changes in railway construction layers were modelled pursuant to the data of the Lithuanian Hydrometeorological Service of January–February 2015 in Vilnius region and the conducted field experimental studies. Ambient air temperature, moisture content in layers and snow cover thickness were assessed. Properties of the materials used to install railway construction layers were identified in the laboratory. Moisture content and temperature in construction layers were measured using sensors installed in the experimental field stand (DRETM II) set up in Slovakia. Modelling results have shown that the greatest temperature difference with a snow cover layer on the top railway construction and without it is 1.2 °C. These data revealed that a snow cover carried out the function of a thermal insulation layer. The railway construction with a snow cover had a lower freezing depth (difference of 0.5 cm). With increasing distance from the top of the ballast layer, the temperature of construction layers with a snow cover approaches the temperature of the construction without a snow cover, i.e. temperatures tend to approximate.

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1. Introduction

In railroad construction one of important elements are ballast and sub-ballast. Railroad ballast has to resist vertical and longitudinal forces, hold the track in position, provide energy absorption for the track, facilitate adjustment of the track geometry, provide immediate drainage of water falling onto the track, reduce pressures on underlying materials by distributing loads, provide energy absorption for the track [1, 2].

Exposed to rail traffic loads, climate and ambient air factors, railway track ballast, sub-ballast and railway bed deform, which in turn leads to the changing track quality index (TQI) [3–5].

The railway sub-ballast layer must ensure an even distribution of rolling stock loads throughout railway sleepers and the ballast layer to the soil bed, prevent ballast rubble and soil from mixing, deformation, drain rain water due to low water permeability, also, prevent it from rising via capillaries and protect the bed soil from frost.

Water occurring in structural layers of the railway track has a major impact not only on the deformation, but also on thermo-technical features of inbuilt construction materials. The moisture content of the track substructure is not constant, but it varies in the course of the year, depending on the amount of downfall (water, snow), temperature and water regime of the body of the track substructure as well as its shape (embankment, cutting, cut) [6, 7].

Considering the increase of train speeds, the determination of the zero isotherm – non-traffic load (climate influence) [8] is a very important task for the railway corridor bodies. The research project, which was done in Slovakia and results presented [9] shows the determination of the position of the zero isotherm in the construction of railway subgrade, where it is possible to state that freezing of a certain construction layer occurs.

In most European countries road weather information systems (RWIS) have been established to reduce the road maintenance costs in winter, to ensure good traffic safety, to inform drivers about poor traffic conditions [10]. The response of permafrost to climate warming differs greatly from that of engineering construction. This difference is mainly caused by permafrost thermal stability [11, 12].

A large amount of research on climate change, its effects on transport and possible solutions has been carried out in different countries (USA [13], Australia [14], Scotland [15], United Kingdom [16]). Canada and other northern countries have not only a problem related to global warming, but also a more frequent freeze-thaw cycle [17]. The assessment of the current effects of extreme weather conditions on transport systems reveals high costs in specific locations [18].

Freezing depth of the railway construction is defined as a distance of zero isotherm ($0\text{ }^{\circ}\text{C}$) from the surface of railway bed. The following factors influence the thermal resistance of the railway construction: temperatures in the winter period characterized most commonly by the frost index (I_m) thermal-insulation features of the railway subgrade structure layers; condition of subgrade surface soil (humidity w , bulk density ρ , granulometric composition, etc.); thickness of snow cover on the railway track.

Maps on the distribution of the depth of frozen ground according to the data of meteorological stations and of RWIS (Road weather information system) show that the deepest zone of frozen ground (120–130 cm) covers the largest part of the territory of Lithuania [19]. Climate of the Baltic region is monitored continuously [20–22]. But the conducted climate change research has shown that at times the ongoing gradual climate warming does not reflect the climate of specific regions [23]. Thus an accurate assessment of each region, or, more accurately, its part, is possible solely by specifically monitoring data of each metrological station. In 1961–2010, the most vivid trend of increasing average air temperature was observed in winter in Lithuania (with the greatest changes being in January). In this time of the year, the highest temperatures were in the Eastern Lithuania. The average annual air temperature also experienced a statistically significant increase throughout the entire territory, while in the fall, just like in the months of May and June, air temperature changed slightly [24].

A snow cover covering the ballast layer in cold climate countries such as Lithuania has a positive impact on thermodynamic processes of railway construction layers. A sufficiently thick snow cover can reduce the freezing depth of construction layers and slow down changes of geothermal parameters of the road.

A snow cover in land transport on roads and railways has a different effect on parameters of vehicle traffic. A snow cover covering the road pavement reduces the wheel grip factor and increases rolling resistance, thus it is either mechanically removed or chemically melted [25]. Snow covering railways is dangerous in northern countries,

when the snow cover thickness is above 1 m. There have been no studies of the effects of a snow cover thickness on thermodynamic processes of railway construction layers conducted in Lithuania so far.

The aim of the work is to model a thermodynamic regime of railway construction layers at variable ambient air temperatures and snow cover, identifying the influence of a snow cover on the freezing depth.

2. Modelling parameters

2.1. Theoretical conception

The solid state (ice lenses) of moisture contained in railway construction layers starts forming in regions where the temperature falls below 0 °C. Depending on the duration of the below-zero temperature period, the freezing depth may vary greatly. Since the moisture content of materials used in railway constructions may differ significantly, the freezing depth may also be different. In addition to temperature changes, other factors include the snow cover thickness and/or precipitation volume, which determine the freezing of construction layers.

In countries or their regions where the volume of precipitation (snow) is sufficiently large [26], snow removal equipment, railway snow-melting systems and special constructions reducing snow accumulation on the railway surface are used [27]. In other regions, where railways are not cleaned, the naturally formed snow cover thickness remaining on the top of the ballast layer stays the same as a railway locomotive ground clearance and the distance between the top of the rails to the ballast layer (about 40 cm) in presence of sufficiently intensive train traffic. This layer may decrease as the moving train may blow off a certain thickness of a snow cover. Thus the maximum thickness remaining on the top construction of railroad rails may be no greater than 30 cm depending on the intensity of train traffic, the used rail and sleeper structures, the environment (whether the construction is installed on a mound or in a pit) and the snow condition [28].

The freezing depth differs depending on how low the negative temperature actually is and the period of time that it stays that low (see Fig. 1). Disregarding the thickness of railway construction layers at temperatures below – 10 °C, the freezing depth should not reach the top of the subgrade construction layer. The snow cover thickness at negative ambient air temperatures should reduce the freezing depth.

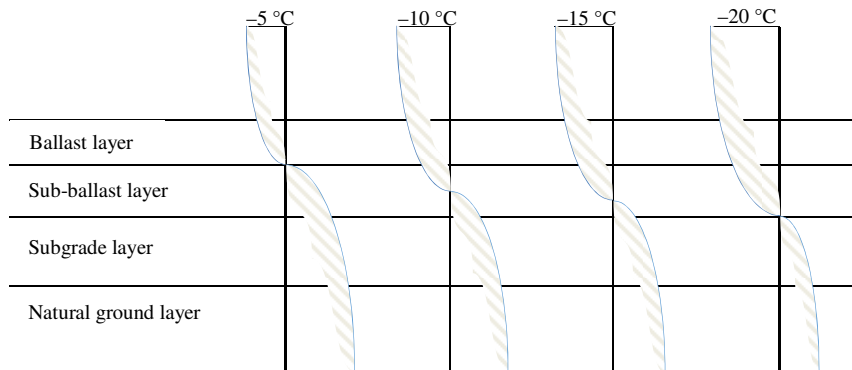


Fig. 1. Theoretical temperature distribution in railway construction during a 5-day period.

With changing temperature regime, when negative temperatures increase above zero, the melting snow on the railway construction surface penetrates to deeper layers. Once the temperature falls below zero once again, the freezing depth may increase if ballast and sub-ballast layers do not perform their hydraulic functions.

2.2. Temperature modelling of multilayer construction

The fact that the national methodology of the selection of sub-ballast layer of the Slovak railway construction built of KG1/KG2 based on the German experience is the same as that in Lithuania [29] indicates that the thickness

of this layer should be installed considering non-traffic load, static and dynamic traffic load, speed and sleeper materials and etc.

In order to be able to use this mathematical model (Fig. 4), it was validated using data received in the experimental stand (DRETM II) Fig. 5. Because of the use of raw materials, technologic processes of layer installation and railway construction geometric parameters similar to or same as those used in railways built in Lithuania, the experimental stand DRETM II Fig. 5 was used. This experimental stand constantly (every 30 min) records ambient air temperature, temperature and moisture content in construction layers and the ambient air temperature.

“SV HEAT” software works on the following principle: it is an indirect determination of the coefficient of thermal conductivity of examined material by the method of no stationary thermal flow and specific thermal capacity. The physical principle of the method is based on one-way propagation of heat conduction in homogeneous materials characterized by the Fourier differential equation [30]:

$$q(x, t) = -\lambda \cdot \frac{\delta T(x, t)}{\delta x}, \quad (1)$$

where: $q(t, x)$ – heat – flow density at the point x and time t , ($\text{W} \cdot \text{m}^{-2}$); λ – coefficient of thermal conductivity, ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$); $T(x, t)$ – temperature at the point x and time t (K).

With the occurrence of actual heat exchange processes in soil, its temperature and heat flow rate change continuously; therefore, the temperature change rate in soil is measured according to the thermal continuity equation) (1):

$$\frac{\delta q(x, t)}{\delta x} = -q \cdot c \cdot \frac{\delta T(x, t)}{\delta t}, \quad (2)$$

where: ρ – specific weight, ($\text{kg} \cdot \text{m}^{-3}$); C – specific heat capacity, ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$).

Thus the application of principles (1) and (2) allows additionally assessing heat exchanges in vertical and horizontal directions and water content therein. Also, the modelling allows assessing the thermal conductivity (λ) and the change of specific heat (C) and soil density (ρ).

The coefficient of thermal conductivity that can be derived from equations (1) and (2):

$$\lambda = 0.249 \cdot \frac{h^2}{\Delta t_c} \cdot \rho \cdot c, \quad (3)$$

where: h is sample thickness (m).

This equation can also be used to calculate the soil freezing depth.

2.3. Climate

Data of January–February of 2015 on temperature distribution in railway construction layers and the freezing depth with changing air factors in Vilnius region were received for modelling purposes from the Lithuanian Hydrometeorological Station (ambient air temperature, Fig. 2a) and snow cover thickness Fig. 3a).

Lithuanian climate can be characterized by a sufficiently frequent drop of above-zero temperatures to below-zero temperatures and vice versa (10 times in 2014 and 11 times in 2015), thus January and February were selected as reference months of 2015, when such temperature changes occurred 5 times (Fig. 2a). Temperature drops from above to below zero and vice versa as well as the water (moisture) content contained in construction layers are factors having a negative effect. Moisture contained in railway construction layers at below-zero ambient air temperatures form ice lenses, which may change geometric parameters of railway structure.

Fig. 2a illustrates average ambient air temperatures T_s , characterizing the entire 24-hour period, which are calculated according to the formula:

$$T_s = \frac{T_7 + T_{14} + 2T_{21}}{4}, \quad (4)$$

where T_7 , T_{14} and T_{21} are temperatures measured at 7.00 a.m., 2.00 p.m. and 9.00 p.m. of Greenwich meantime 2 m above ground.

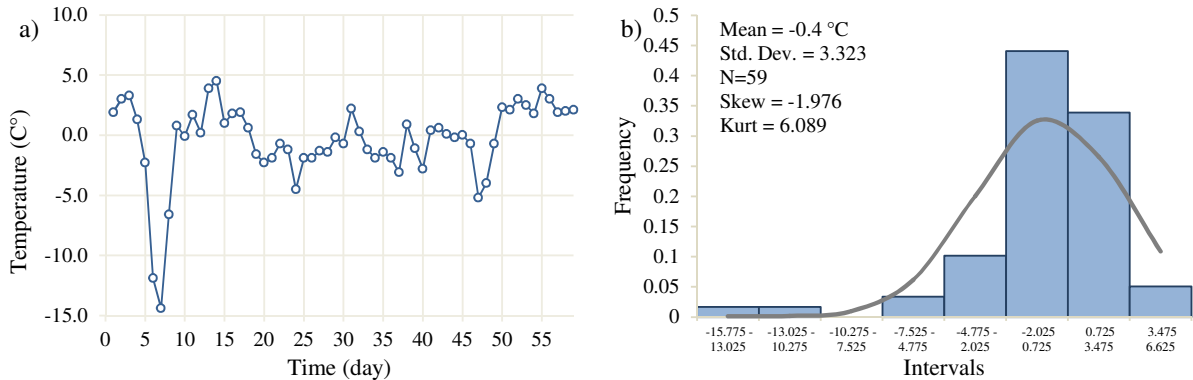


Fig. 2. Change of ambient air temperature and statistical indicators in railway sections in the examined period (January–February of 2015): a – ambient air temperature; b – statistical indicators – snow cover thickness change.

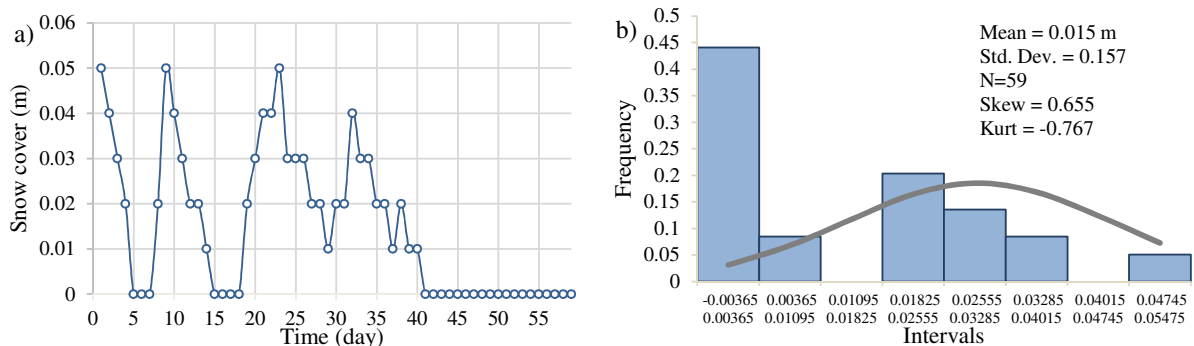


Fig. 3. Snow cover thickness change and statistical indicators in railway sections in the examined period (January–February of 2015): a – snow cover thickness change; b – statistical indicators.

The frost index I_m is the most common characteristic which is used when considering the thermal regime and the assessment of the railway subgrade from the point of view of its protection against frost. The frost index is not a constant value each year. It depends directly on air temperature, which is also influenced by several factors. It is possible to mathematically express the influence of individual factors on the size of the index to only a certain extent. The more precise determination of the frost index is possible only by the direct measuring of temperatures at particular meteorological stations. Frost index is calculated summing negative temperatures, to get biggest negative temperature index ($I_m = -147.1$ °C of this period).

In this paper the frost index I_m is given by summing up the medium day air temperatures T_s in the winter period according to the equation (5):

$$I_m = \sum_{t_z}^{t_k} T_s \cdot \quad (5)$$

Thermal regime of the railway subgrade is defined as a course of thermal changes of individual structural layers and soil, thermal radiance and air temperature changes in the day or during a year. Freezing depth of the railway construction h_{pr} is a very important characteristic in this sense. Other properties used for climate modelling are illustrated in Table 1.

Table 1. Different phase of air and water properties.

Properties	Value
Water Thermal Conductivity	49248 J/(day·m·C)
Ice Thermal Conductivity	194400 J/(day·m·C)
Dry Air Thermal Conductivity	2073.6 J/(day·m·C)
Vapor Thermal Conductivity	466560 J/(day·m·C)
Volumetric Water Heat Capacity	4187000 J/(m ³ ·C)
Volumetric Ice Heat Capacity	2094000 J/(m ³ ·C)
Volumetric Air Heat Capacity	1173.26 J/(m ³ ·C)
Volumetric Vapor Heat Capacity	186 J/(m ³ ·C)
Density of Water	1000 kg/ m ³
Density of Ice	920 kg/ m ³
Density of Air	1.205 kg/ m ³

Note: Phase change parameters: Latent Heat Fusion of Water, $L_f = 3,34\text{E} + 08 \text{ J/m}^3$, Latent Heat of Vaporization of Water, $L_v = 2,5\text{E} + 09 \text{ J/m}^3$.

The higher is the moisture content in construction layers, the greater is the influence of negative temperatures. Water contained in construction layers converts to the solid state upon freezing, which in turn expands and destructs particle compounds formed in construction layers, which may lead to changed geometric parameters of the entire road.

2.4. Materials properties

Typical (most widely used) construction used when building railways in Lithuania [29] and Slovakia [31–33] was chosen in the modelling. It consists of a roadbed built of a sand mixture (55 cm-thick), KG1 layer built of mixture of 0/32 mm mineral materials (45 cm-thick) and a ballast layer made of 0/63 mm granite rubble (50 cm-thick). Natural soil with vegetation on the sides of the roadbed was spread in a 10-cm thick layer. 150 cm-thick natural soil for laying the railway construction was chosen for the modelling. All geometric parameters of the railway construction are presented in Figure 4.

In order to obtain temperature distribution in layers in the modelling software SV HEAT, the necessary information on soils is presented in Table 2. Thermometers were inserted in the construction designed in the software (11...39) in order to obtain temperature results at specific points (Fig. 4). Specific Heat Capacity of Solid Component and Thermal conductivity standard values are presented [34] in light of the data of the technical construction regulation [35]. But in order to receive more accurate modelling results, the thermal conductivity indicator was determined by in kind studies of a specific material.

Dry soil density was determined in application of standard methods [36]. Volumetric water content and initial temperature in layers were determined under actual conditions from the experimental stand (DRETM II) Fig. 5. Phase Change temperature from/to were set by SV HEAT software algorithm.

The use of standard parameters presented in standards and normative documents does not allow assessing properties of a specific material/layer. Thus having used properties of materials received in experimental research, the modelling result of a construction made of specific materials is obtained.

This allows adjusting an individual model of each construction by introducing amendments received from actual construction measurements.

3. Temperature changes in the construction with and without a snow cover

The construction discussed in Chapter 1.3 was selected for modelling, using a snow cover, which changed according to the presented graph (Fig. 3a), in one case and no snow cover – in another case. The received temperature distribution in layers is presented in Fig. 6 during the coldest period (8.6 day).

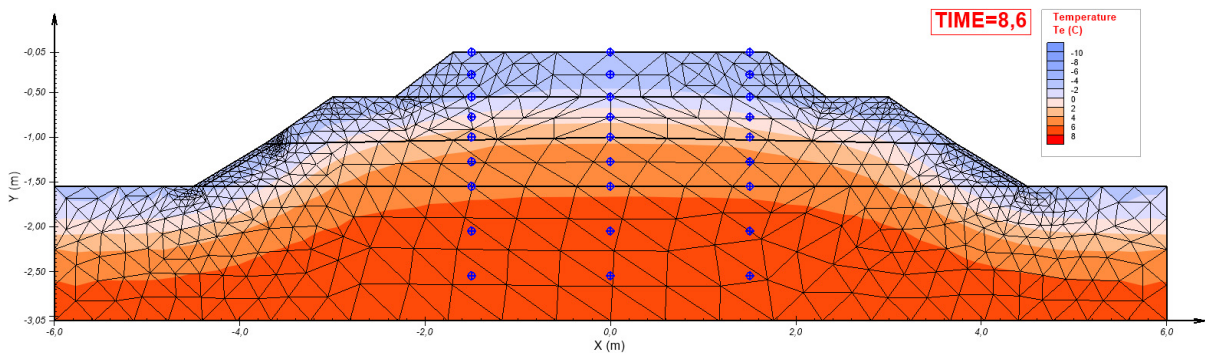
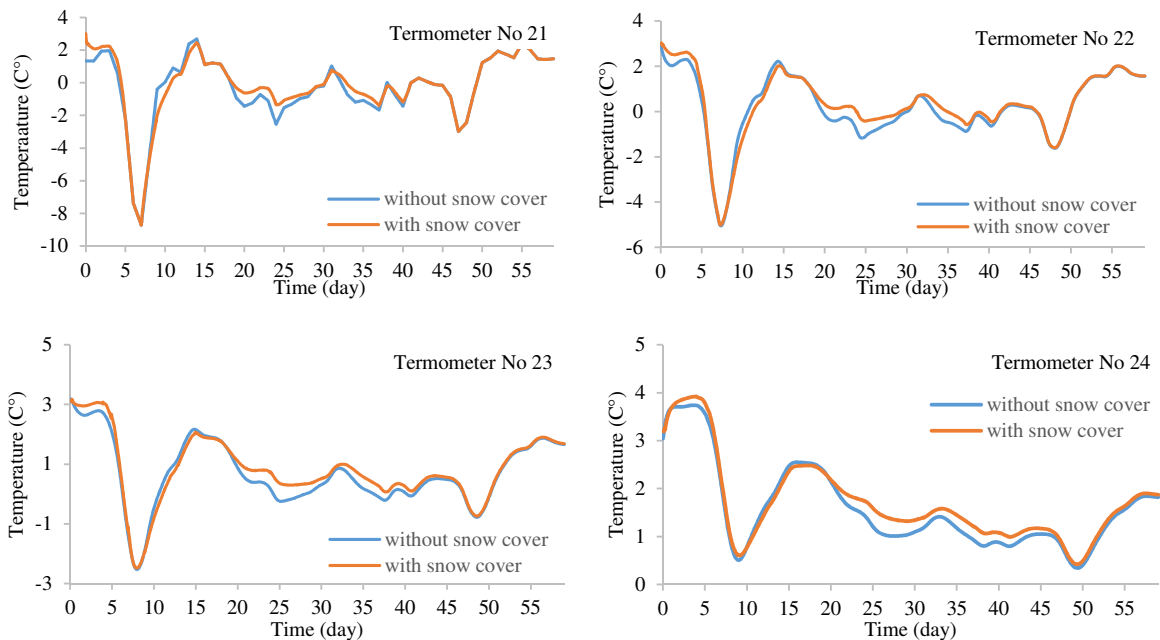


Fig. 6. Temperature distribution in railway construction during modelling process.

Having analyzed the processes occurring in construction layers and temperature distributions, temperature differences in different layers and their contact zones are illustrated in Fig. 7. Temperature values were measured in central thermometers (21, 22, 23, 24, 25, 26, 27, 28, 29 – Fig. 3), at the moment of time $t = 0.5$ h (Fig. 7).



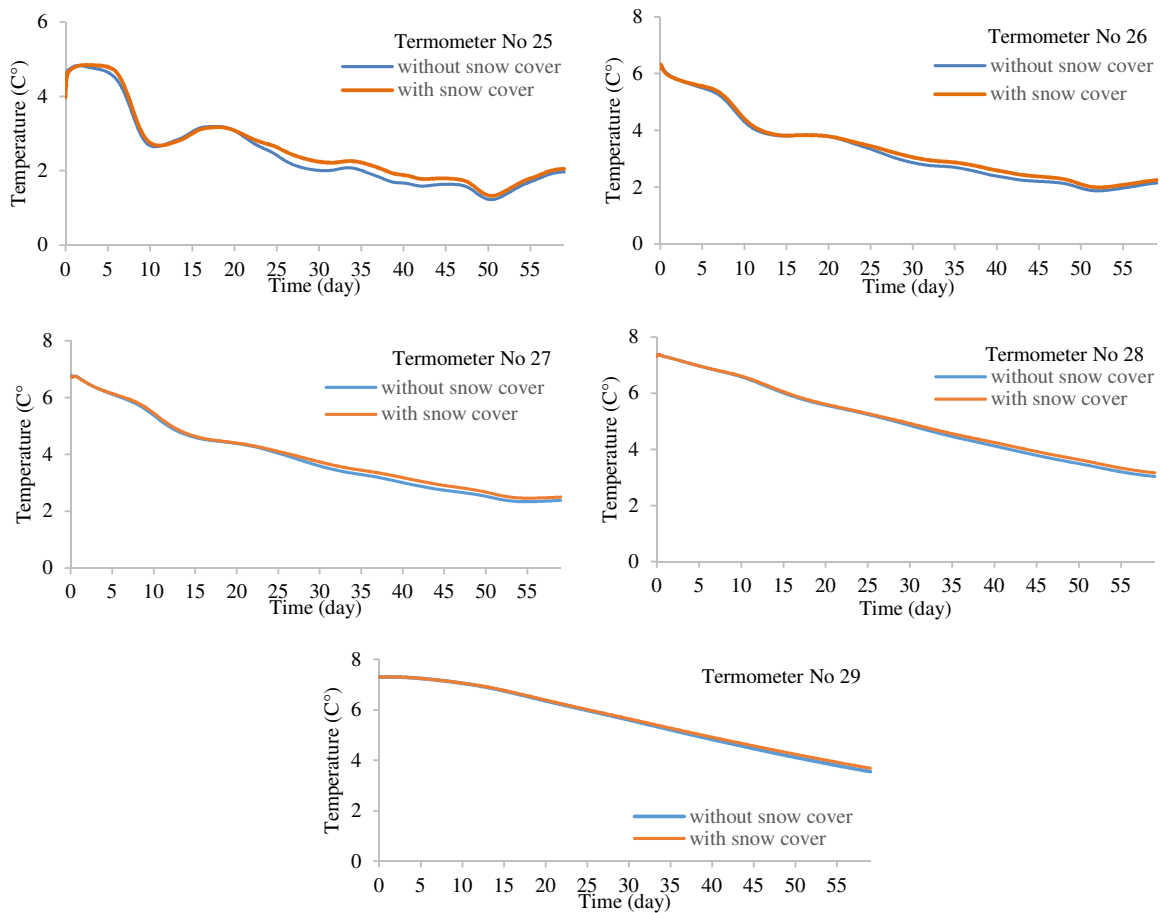


Fig. 7. Temperature distribution in construction layers during modelling period.

The modelling results show that the freezing depth in construction with a snow cover was greater (61.62 cm) compared to the construction without a snow cover (60.07 cm) at the moment of time (8.6 day), when the ambient temperature increased and reached -14.4°C and the snow thickness was the greatest (0.05 m). The temperature distribution graphs presented in Fig. 7 reveal that the temperature in railway construction layers in modelling without a snow cover was equal to that in modelling with a snow cover or lower. The maximum difference (1.2°C) was received on the surface of the ballast layer on the 24th day, with a respective difference of 1°C in the middle of the ballast (Fig. 7). The difference at the bordering plane of the ballast layer and sub-ballast layers received on the 25th day was 0.6°C .

The analysis of temperature values recorded by vertical thermometers allows stating that the protective layer meets the set requirements – the freezing depth did not reach the subgrade layer. The received temperature values (Fig. 7) show that with increasing vertical distance from the land surface, the impact of the snow cover on temperature changes has increasingly less influence (the temperature difference decreases). Also, with ambient air temperature changing non-linearly, the dependence becomes increasingly linear as the layers get deeper.

4. Conclusions

1. Thermodynamic railway processes were modelled using the experimental stand (DRETM II), laboratory research data and data from the Lithuanian Hydrometeorological Station. The change of temperatures of construction layers was determined in presence of the changing snow cover thickness and without it.

2. At the greatest snow cover thickness (of 5 cm), the difference between freezing depths was about 1.5 cm when comparing the same construction with and without a snow cover.
3. The maximum difference (1.2 °C) was received on the ballast layer surface on the 24th day, with the difference in the middle of the ballast layer being 1 °C and at the border of ballast and sub-ballast layers being 0.6 °C. The lower the ambient air temperature, the lower is the influence of the snow cover on the ballast layer on all railway layers.
4. The data of this experimental research and modelling may also be used to improve normative railway track construction design documents.

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