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EXPERIMENTAL MONITORING AND NUMERICAL MODELING OF THE THERMAL REGIME OF SELECTED TRACK SUBSTRUCTURES

Summary. The initial part of the paper characterizes major research activities at the Department of Railway Engineering and Track Management (DRETM), Faculty of Civil Engineering, University of Žilina. Subsequently, it outlines the state of art in the field of track substructure dimensioning for the non-traffic load in Slovakia and abroad. The second part of the paper deals with the method of collecting input parameters for numerical modeling of the track substructure freezing using SoilVision software. The following part of the paper compares the results of the track substructure freezing obtained by experimental measurements and numerical modeling in the winter of 2016/2017. The final part of the paper focuses on the results of numerical modeling of the track substructure freezing in terms of the climatic conditions typical of railway infrastructure in the Slovak territory. Moreover, it presents a design of a modified nomogram for determination of the necessary thickness of the frost-susceptible subgrade surface layer and characterizes further related research activities planned to be implemented at the Department in the near future.

1. INTRODUCTION

After the accession of the Slovak Republic (SR) to the European Union (EU), the Slovak Railways started to modernize their main corridor tracks. The present knowledge of the track structure dimensioning confirms that to guarantee the quality and safety of railway tracks, their design has to consider some significant characteristics. Besides the quality and efficiency of particular superstructure components, these properties include track substructure composition, physical and mechanical properties of substructure materials, and track drainage.

As science and technical development are a constant source of knowledge, materials, and construction technology, DRETM researchers have been focusing their scientific activities on deepening and updating knowledge in the field of track substructure dimensioning for the non-traffic load (effects of climatic factors) for more than 15 years. Their main objective was to update the obsolete track substructure dimensioning methodology [1], which was based on findings from the 1960s and the 1970s.

Moreover, the methodology needs to be updated due to recent climatic changes (an increase in the average annual air temperature and a decrease in snowfall rates and intensity) and application of new building materials in the structural layers of the track substructure (predominantly replacement of gravel-sand by crushed aggregate and also new thermal insulation materials). The problem of the influence of climatic effects on the track substructure has been studied by several foreign researchers, for example in Canada [2-5], Japan [6], England [7], Norway [8,9], United States of America [10], Poland and Germany [11]. When studying the problem of railway track dimensioning for the non-traffic load, some of the researchers in the neighboring countries have been inspired by the UIC ORE research carried out at the Trondheim University in the 1970s [12, 13].

2. BASIC PARAMETERS FOR DIMENSIONING AND MODELING OF THE THERMAL REGIME OF THE TRACK SUBSTRUCTURE

To obtain a realistic image of the track substructure freezing and for the purposes of numerical modeling of climatic effects on the depth of freezing of the structure for any course of a winter period, it is necessary to identify and define the values of several parameters that influence the process. Generally, these parameters include the following:

- material characteristics (physical, mechanical, and thermotechnical properties) of particular track substructure layers (thermal conductivity coefficient, volumetric heat capacity, bulk density, moisture, temperature, etc.),
- climatic characteristics (mean daily air temperatures, average annual air temperatures, frost index, etc.), and
- snow cover thickness.

To enable the identification and specification of these characteristics, an experimental stand, a railway track model in a 1:1 scale, was built. This stand will be described in Part 2. Due to the research objective – updating the track substructure dimensioning methodology for the non-traffic load, it was necessary to verify the particular climatic characteristics, input material characteristics of structural layers of the track substructure and their influence, and also the influence of snow cover on the depth of railway track (track substructure) freezing.

2.1. Experimental monitoring of thermal regime of the track substructure in the track structure model

The Department of Railway Engineering and Track Management (DRETM) has been involved in research activities including the problem of monitoring the influence of the non-traffic load on the track substructure (railway track) since 2003 when the Experimental stand DRETM I was built. This experimental stand represented a railway track model in the 1:1 scale, with a built-in track substructure no. 2. Its track superstructure was built at the level of the surrounding terrain. According to [1], the track substructure no. 2 consists of a ballast bed and a protective (foundation) layer, placed on the subgrade surface, which is frost and water susceptible (the subgrade surface soil is frost-susceptible and poorly permeable). The experimental monitoring of the thermal regime of the track substructure at the Experimental stand DRETM I was completed in 2016/2017. The results of experimental measurements, conducted at the stand, were analyzed and published in a scientific paper [14].

Since 2012, the DRETM has been able to use the Canadian software *SoilVision*, which enables numerical modeling of the thermal regime of railway tracks with various track substructure compositions under the influence of diverse climatic factors. To conduct relevant numerical modeling and its subsequent comparison to the results of experimental measurements at particular structures of the Experimental stand DRETM, several input data were necessary. These included the physical, mechanical, and thermal properties of built-in construction materials and some climatic characteristics of the environment where the respective experimental stand was located.

Considering that these data were not available and that the Department had to move to a new university campus, a decision was taken to build a new experimental stand. This new stand was not only supposed to provide the required input data but also to verify the thermal regime of the railway track for various track substructures and for different courses of winter periods.

After building the new experimental stand – a railway track model in a 1:1 scale in 2012, in the winter of 2013/2014, the first measurements of the thermal regime of railway tracks and identification of the achieved depth of freezing of the railway substructure in real winter conditions were carried out. In the first stage (until the beginning of the winter of 2013/2014), two measuring profiles, each 3000 mm long, were built in this experimental stand (under the working name Experimental stand DRETM).

The measuring profile no. 1 represents the track substructure no. 2. Here, a crushed aggregate layer, fr. 0/31.5 mm, 450 mm thick, is placed on the subgrade surface of an embankment. On this layer, the track ballast, fr. 31.5/63 mm, and the track skeleton are placed – Fig. 1. The structural thickness of the so-called protective layer was dimensioned in compliance with the valid methodology stated in [1].

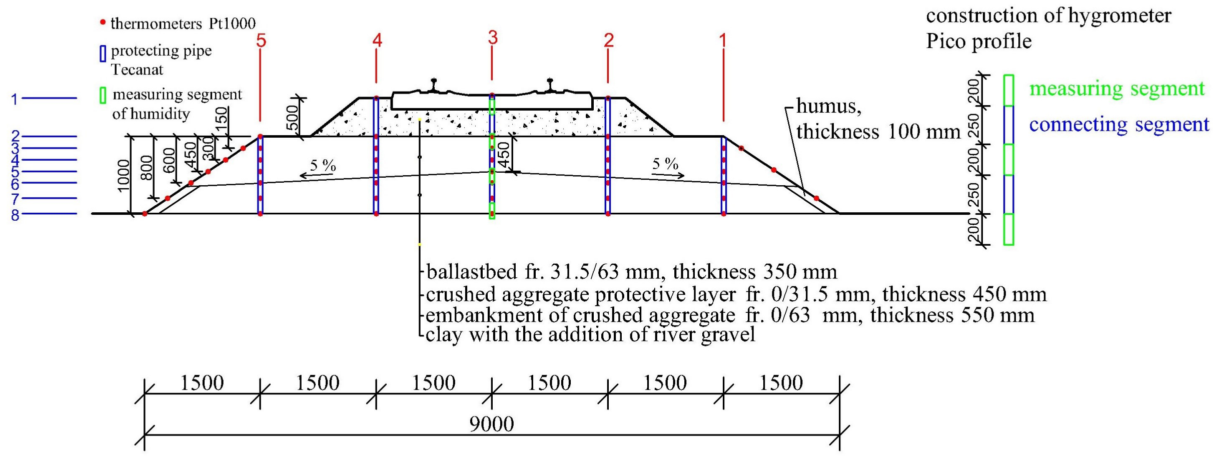

Fig. 1. Experimental stand DRETM – measuring profile no. 1

In 2017 the Experimental stand DRETM was completed. It includes 6 measuring profiles; 3 of these include various thermal insulation materials (Foam concrete, Liapor concrete, Styrodur) in their substructures. Numerical modeling of these measuring profiles will be the subject of further research activites.

In contrast to the first railway track model (Experimental stand DRETM I), at the Experimental stand DRETM in all its profiles, it is possible to monitor the course and changes of moisture of all built-in materials by a non-destructive method (time-domain reflectometry - TDR). Moreover, using thermal sensors, which form a dense network in all the track profiles, it is possible to monitor the thermal regime of the track substructure or the entire railway track. The results of experimental monitoring of the track substructure moisture at the Experimental stand DRETM have been published in [15].

For numerical modeling of the respective structures in the *SoilVision* software, it was necessary to determine the thermotechnical parameters of materials built in particular structural layers of the Experimental stand DRETM (thermal conductivity coefficient λ and specific heat capacity c); thus, these parameters were determined in the DRETM laboratory. The measurement methodology and achieved results were published in [16]. The overview of climatic characteristics, based on monitoring at the Experimental stand DRETM, as well as the analysis of the so-far recorded coldest winter in 2016/2017, are stated below.

2.2. Overview and analysis of results of experimental measurements at the Experimental stand DRETM

The primary characteristic of the thermal regime of the track substructure (railway track) in winter is the achieved depth of freezing D_F (position of the zero isotherm in the track substructure). This characteristic is not only affected by the structural composition of the track substructure and the thermotechnical properties of built-in materials but also by the initial temperature of track substructure materials before the freezing process and the course and intensity of frost in winter.

The determination of the zero isotherm position in the track substructure (railway track) is possible using thermal sensors built in the experimental stand structure. The measuring profile no. 1 contains approximately 50 thermal sensors, installed in particular structural layers of the railway track model and in its subgrade (Fig. 1). These sensors measure the real temperature in their particular locations every 30 minutes. To monitor climatic characteristics, 1 thermal sensor, which measures the air temperature 2.0 above the terrain surface, was built in for all measuring profiles. Tab. 1 demonstrates the monitored climatic characteristics ($\theta_{s,max}$ – maximum mean daily temperature during the winter period, $\theta_{s,min}$ – minimum mean daily air temperature during the winter period, θ_m – average annual air temperature, I_F – air frost index, I_{FS} – ait frost index on the measuring profile surface – ballast bed surface), as well as the resulting track substructure depth of freezing D_F of measuring profile no. 1 of the DRETM stand in the winter seasons of 2013 to 2018.

Table 1

Climatic characteristics obtained from measurements
at the Experimental stand DRETM

Winter period	$\theta_{s,max}$ (ºC)	$\theta_{s,min}$ (ºC)	θ_m (ºC)	I_F (ºC, day)	I_{FS} (ºC, day)	D_F (m)
2013/2014	10.45	-11.7	9.6	-38	-22	0.41
2014/2015	8.5	-10.8	10.2	-77	-32	0.41
2015/2016	5.5	-10.2	9.9	-99	-72	0.46
2016/2017	4.2	-19.0	9.2	-284	-245	0.65
2017/2018	9.7	-11.2	9.0	-107	-66	0.56

It is typical of all the obtained values that during the winter seasons of 2013 to 2018, snow was always removed from the railway track surface (surface of both measuring profiles), with the aim of simulating the maximum effects of frost on track substructure materials. It means that the temperature values achieved in the DRETM profile structures were not affected by thermal insulation effects of a snow cover. Thus, the final depth of track substructure freezing in the given climatic conditions can be considered the maximum.

As can be seen in Tab. 1, the coldest winter, when the zero isotherm penetrated the ballast bed and the sub-ballast upper surface, was the winter of 2016/2017.

The obtained results of experimental monitoring conducted at measuring profile no.1 of the Experimental stand DRETM (Tab. 1) indicate that the air frost index, calculated from the air temperature values directly affecting the ballast bed surface, is approx. 45 % – 85 % of the value of the air frost index measured 2.0 m above the terrain surface of measuring profiles.

As mentioned above, during all winter periods, the snow cover, which would cause an even greater difference between the frost index values, was removed from the entire railway track model surface. The achieved depth of freezing of the track substructure in measuring profile no. 1 was predominantly affected by the actual course of the winter period. The greatest depth of freezing was achieved when the long frost period was not interrupted by a warm period (days with a positive average daily air temperature). Such an interruption of a frost period by a warm period could be observed in the winter of 2016/2017, when the greatest depth of freezing D_F = 0.65 m (I_F = -278 ˚C, day) was achieved on February 1, 2017, but the maximum air frost index I_F = -284 ˚C, day, was only achieved on February 14, 2017, with the corresponding depth of freezing D_F = approx. 0.50 m. It was also interesting to compare the winter periods of 2013/2014 and 2014/2015 when the depth of freezing value in measuring profile no. 1 was identical (D_F = 0.41 m). However, the achieved air frost index of these winter periods differs in approx.100 % (I_F = -38 ˚C, day vs -77 ˚C, day). These values imply that the resulting depth of freezing D_F is not only affected by the achieved air frost index I_F but also by the amount of accumulated heat in the railway track before the actual freezing process and by the course of the winter period (number and intensity of frost and thaw periods). In respect to temperatures in the measuring profile structures of the Experimental stand DRETM before the freezing process, it can be stated that before the winter of 2013/2014, the substructure temperature was 1.5 ˚C lower than in the winter of 2014/2015. In terms of the recorded number of frost periods and their course, in the winter of

2013/2014, only 1 more significant period was recorded. In the winter of 2014/2015, 1 more significant frost period was again recorded, but it was interrupted by several short warming periods. All the facts mentioned above considerably affected the zero isotherm position in measuring profile no. 1 of the Experimental stand DRETM and must thus be considered in the nomogram design of dimensioning the structural thickness of the protective layer of subgrade surface.

3. NUMERICAL MODELING OF THE THERMAL REGIME OF THE TRACK SUBSTRUCTURE MODEL

The Canadian software *SoilVision* [17], specifically *SVHeat* [18], enables to obtain relatively accurate results of the track substructure freezing compared to real achieved (measured) values. A basic prerequisite, however, is the availability of relevant input parameters for real modeling of the thermal regime of the respective track substructure (railway track).

Obtaining all necessary input parameters of construction materials built in the track substructure and of climatic factors affecting the railway track during the winter period is a complex process in terms of time and financial requirements. The collection of available input data has been described in detail in Chapter 2. First, a comparison of the real depth of freezing D_F of the railway track, obtained at the Experimental stand DRETM, with the depth of freezing determined by numerical modeling (see Part 3.1), was conducted. Subsequently, a nomogram for the thickness of the protective crushed aggregate layer was prepared (see Part 3.2).

3.1. Comparison of results of the numerical modeling to real measured values of the track substructure freezing

To numerically model the thermal regime of the railway track, it was necessary to create its model using the coordinates (Fig. 2), enter the locations of temperature monitoring in the model (blue dots – locations of actually installed thermal sensors - thermometers), and to specify the input parameters for numerical modeling (Tab. 2).

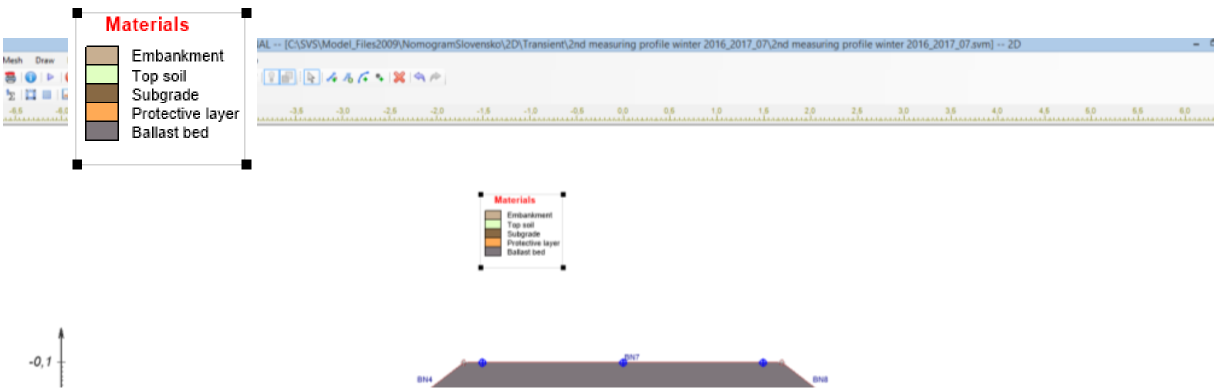

Fig. 2. Model of the Experimental stand DRETM – measuring profile no. 1

In numerical modeling, the course of the winter period 2016/2017 was applied. As mentioned above, this winter period was the coldest period during the thermal regime monitoring at the Experimental stand DRETM. In the numerical model, this winter period is represented by 96 days.

The first day of the winter of 2016/2017 in a numerical model (TIME=1) is represented by the date November 26, 2016, and the last day in the model (TIME=96) by the date March 1, 2017. This time delimitation is based on real measured values of the course of the winter period of 2016/2017. The day of November 26, 2016, is the time moment of 3 days before the first negative mean daily air temperature $\theta_{s,}$ (beginning of the frost period) and the day March 1, 2017, is 3 days after the last mean negative daily air temperature $\theta_{s,}$ (end of the frost period). Climatic characteristics in the model were entered by mean daily air temperatures θ_s. The conversion to the surface temperature (on the ballast bed surface) θ_{bb} was carried out by factor $n_f = 0.8$ (the temperature on the ballast bed surface was approx. 80 % of the air temperature). The output of numerical modeling of the thermal regime for the values in Tab. 3 is the identification of the depth of freezing D_F of the track substructure (position of the zero isotherm).

Table 2

Input parameters of numerical modeling

Structural part/characteristics	**Ballast bed (clean)**	**Protective layer**	**Embankment**	**Embankment subgrade**	**Slope protection**
Layer temperature (˚C)	8	8	10	11	8
Moisture w_m (%)	1,3	6	5	20	20
Bulk density in a dry state ρ_0 (kg.m^{-3})	1908	1928	2090	1646	1320
Specific heat capacity in a dry state c_0 (J.kg^{-1}.K^{-1})	980	1088	1050	1495	–*
Thermal conductivity coefficient λ (W.m^{-1}.K^{-1})	0.67	1.93	1.42	1.05	1.12 (1.35**)

Note: * value entered by the heat capacity, ** value of a frozen material

The penetration of the zero isotherm in the model structure is demonstrated in Fig. 3, which shows the 68th day of numerical modeling of the track substructure freezing, where the achieved depth of freezing $D_F = 0.67$ m. This depth was also the maximum depth of structure freezing in the measuring profile no. 1 of the Experimental stand DRETM in the winter of 2016/2017.

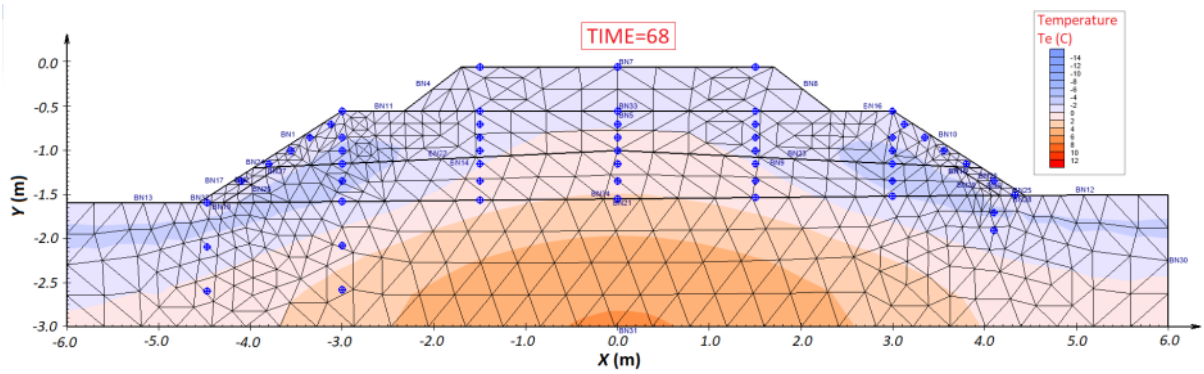

Fig. 3. Achievement of the maximum depth of freezing in the measuring profile no. 1 ($D_F = 0.67$ m)

The position of the zero isotherm in the model is located at the boundary between the light orange and light blue color. The achieved difference compared to the real depth of freezing identified in the railway track model is only 0.02 m (Tab. 1). As the *SoilVision* (*SVHeat*) software provides an overview of reached temperatures in the model on particular days in the selected locations of monitoring (blue dots), it is also possible to conduct their comparison to the real temperatures at the Experimental stand DRETM. The differences in temperatures ($\Delta\theta$) of modeled (θ_{SVH}) and actual measured temperatures on particular days of the monitored winter period (θ_{23}, θ_{53}, θ_{83}) are demonstrated in Tab. 3. The first number in the thermometer marks the row (2 – sub-ballast upper surface, 5 – lower edge of the protective layer - approx. center of the embankment body, 8 – lower edge of the embankment body) and the second number marks the column (3 – rail axis) of the experimental stand structure.

Table 3

Comparison of real measured and modeled temperatures
for the measuring profile no. 1 during the winter of 2016/2017

Date (Day of the winter period)	θ_{23} (°C)	θ_{SVH} (°C)	$\Delta\theta$ (°C)	θ_{53} (°C)	θ_{SVH} (°C)	$\Delta\theta$ (°C)	θ_{83} (°C)	θ_{SVH} (°C)	$\Delta\theta$ (°C)
25/12/2016 (30)	2.75	2.68	**-0.07**	3.61	4.05	**+0.44**	6.04	6,06	**+0.02**
04/01/2017 (40)	1.85	1.78	**-0.07**	2.21	2.74	**+0.53**	4.99	5,17	**+0.18**
14/01/2017 (50)	-0.20	-0.16	**+0.04**	0.86	1.38	**+0.42**	3.65	3,71	**+0.06**
24/01/2017 (60)	-0.19	-0.14	**+0.05**	0.61	0.91	**+0.30**	2.95	2,71	**-0.24**
03/02/2017 (70)	-0.18	-0.18	**±0.00**	0.39	0.54	**+0.15**	2.45	2,07	**-0.38**
13/02/2017 (80)	0.28	0.13	**-0.15**	0.4	0.56	**+0.16**	2.2	1,86	**-0.34**

Tab. 3 clearly shows very good compliance between the measured values of temperature of the Experimental stand DRETM and the values obtained by numerical modeling of the thermal regime of railway structure (track substructure) in the place of the measuring profile no. 1. The maximum difference in these temperatures reached the value of 0.53 °C on January 4, 2017.

3.2. Updating the design nomogram in the track substructure dimensioning methodology for the non-traffic load for the needs of Slovak Railways

After obtaining a set of input data, presented above, the nomogram for the thickness of the protective crushed aggregate layer could be updated. Before the actual numerical modeling, it was necessary to create a railway track model using coordinates. The composition of the structural layers was selected as the most adverse possible, which means that the railway structure is an embankment with a clay subgrade – Fig. 4.

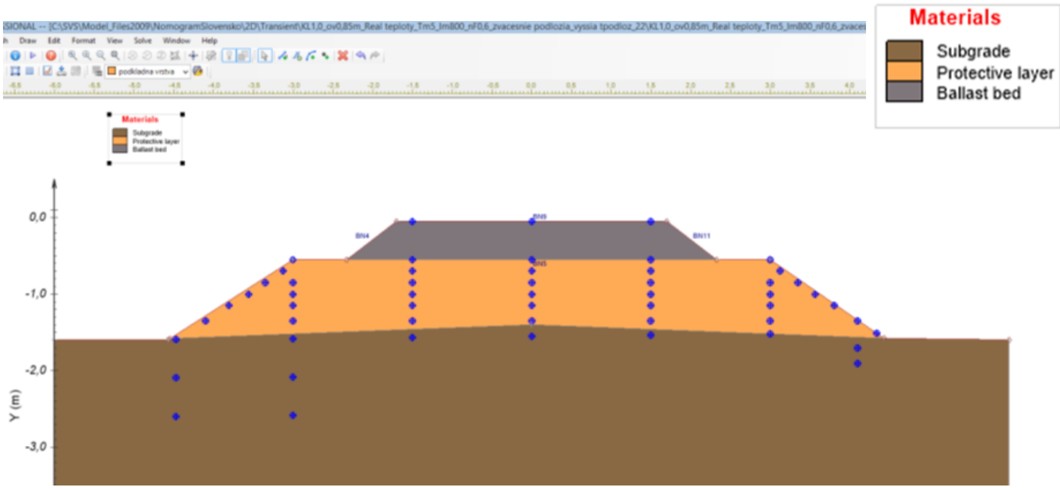

Fig. 4. Railway track model

Fig. 4 demonstrates the respective track model used for numerical modeling of the most adverse climatic conditions (I_F = 800 ˚C, day, and θ_m = 5 ˚C). To cover the cases of other, less adverse climatic conditions, the track models differed in the protective layer thickness, which varied on the basis of achieved depth of the track substructure freezing I_F (thickness of the protective layer t_{pl} rounded up 50 mm upwards based on the achieved depth of the track substructure freezing D_F).

The following step involved the specification of input parameters of numerical modeling, specifically material characteristics and climatic characteristics of the environment – Tab. 4.

Table 4

Input parameters of numerical modeling

<table>
<tr><th>Structural part/characteristics</th><th colspan="2">Ballast bed (polluted – approx. 6 %)</th><th colspan="2">Protective layer</th><th colspan="2">Subgrade</th></tr>
<tr><td colspan="7">Material characteristics</td></tr>
<tr><td>Temperature (°C)</td><td colspan="2">2</td><td colspan="2">5</td><td colspan="2">7</td></tr>
<tr><td>Moisture w_m (%)</td><td colspan="2">4</td><td colspan="2">6</td><td colspan="2">26</td></tr>
<tr><td>Specific heat capacity c_0 ($J.kg^{-1}.K^{-1}$)</td><td colspan="2">980</td><td colspan="2">1088</td><td colspan="2">1495</td></tr>
<tr><td>Bulk density ρ_0 ($kg.m^{-3}$)</td><td colspan="2">1908</td><td colspan="2">1928</td><td colspan="2">1646</td></tr>
<tr><td>Thermal conductivity coefficient λ ($W.m^{-1}.K^{-1}$)</td><td colspan="2">1.00</td><td colspan="2">1.93</td><td colspan="2">1.55</td></tr>
<tr><td colspan="7">Climatic characteristics</td></tr>
<tr><td>Average annual air temperature θ_m (°C)</td><td>5.0</td><td>6.0</td><td>7.0</td><td>8.0</td><td>8.5</td><td>9.0</td></tr>
<tr><td>Air frost index I_F (°C, deň)</td><td>-300</td><td>-400</td><td>-500</td><td>-600</td><td>-700</td><td>-800</td></tr>
<tr><td>nf factor*</td><td>0.80</td><td>0.75</td><td>0.70</td><td>0.65</td><td>0.60</td><td>0.55</td></tr>
</table>

Note:* for the period 'during the year' (between winter periods) nf = 1.15 value was applied

For numerical modeling, the year 1986 and the course of the winter period 1986/1987 were applied (the coldest winter period in terms of the achieved value of the air frost index). In the model, this period is represented by 452 days. It was selected due to the achieved average annual air temperature θ_m and the air frost index I_F. The first day in the model (TIME=1) is represented by the date January 1, 1986, and the last day in the model (TIME=452) by the date March 28, 1987, (10th day after the last negative mean daily air temperature θ_s). This time delimitation is based on real measured values of mean daily air temperatures θ_s. The time period TIME=1 to TIME=365 represents the average annual air temperature θ_m of a selected location, and the time period TIME=333 to TIME=442 is the considered 110-day frost period – period for determining the air frost index value I_F. The data were provided by the Slovak Hydrometeorological Institute for the municipality Spišské Vlachy, where the frost index reached approx. -800 ˚C, day, which is the maximum frost index for the Slovak territory. Climatic characteristics were entered by mean daily air temperatures θ_s, and the conversion to the surface temperature θ_{bb} (temperature on the ballast bed surface) was conducted via the n_f factor (see Tab. 4). The output of numerical modeling of the thermal regime of the tested track structure for values in Tab. 4 is the identification of the track substructure freezing D_F (position of the zero isotherm).

To depict the penetration of the zero isotherm in the track structure, a model representing the effects of most adverse climatic conditions (I_F = -800 ˚C, day, and θ_m = 5 ˚C) was selected. At the same time, the model was exposed to the effects of most adverse material conditions (adverse water regime – maximum saturation of track substructure materials) - Fig. 5. Fig. 5 depicts the 407th day of the thermal regime of the same track model when the reached depth of freezing D_F = 1.31 m was, in this case, the maximum depth of freezing of the track substructure $D_{F,max}$. It is necessary to point out that the frost period was interrupted by one warm period (days with positive mean daily air temperature

θ_s), from day 405 to day 416 (TIME=405-416), and the maximum air frost index value I_F = -800 ˚C, day was reached on day 442 (TIME=442).

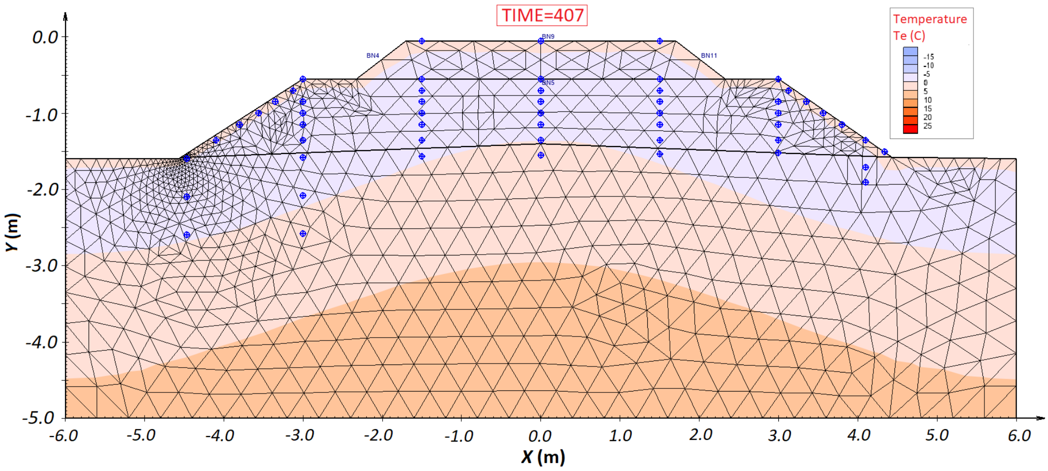

Fig. 5. Achieving the maximum depth of freezing in the model ($D_{F,max}$ = 1.31 m)

The position of the zero isotherm in the model for numerical modeling is at the boundary of light orange and light blue color. The depths of freezing of the track substructure D_F for different, less adverse climatic characteristics (considered frost indexes lower than -800 ˚C, day, and the average annual temperatures higher than 5 ˚C) were determined in the same way, but the thickness of the protective layer in the model varied (see Tab. 5). The resulting values of the depth of freezing D_F depending on various climatic conditions (considered the frost index and the average annual air temperature), as well as required values of the protective layer thickness t_{pl} applied in numerical modeling, are demonstrated in Tab. 5.

Table 5

Resulting parameters of the numerical modeling

Thickness of the protective layer* t_{pl} (m)	**Average annual air temperature** θ_m (˚C)	**Air frost index** I_F (˚C, day)	***nf* factor value**	**Depth of freezing** D_F (m)
0.25	9.0	-300	0.80	0.708
0.35	8.5	-400	0.75	0.825
0.45	8.0	-500	0.70	0.932
0.60	7.0	-600	0.65	1.053
0.65	6.0	-700	0.60	1.141
0.85	5.0	-800	0.55	1.309

Note:* in the numerical model

Based on the values from Tab. 5, a design nomogram for determination of the structural thickness of a protective crushed aggregate layer was prepared – Fig. 6.

If the structural thickness of the ballast bed (t_{bb} = 500 mm), stated in Fig. 6, is added to the values of the thickness of the protective layer, a relationship for calculation of the total depth of freezing of the track structure is obtained:

$$D_F = -0.0012 I_F + 0.3545 \quad (1)$$

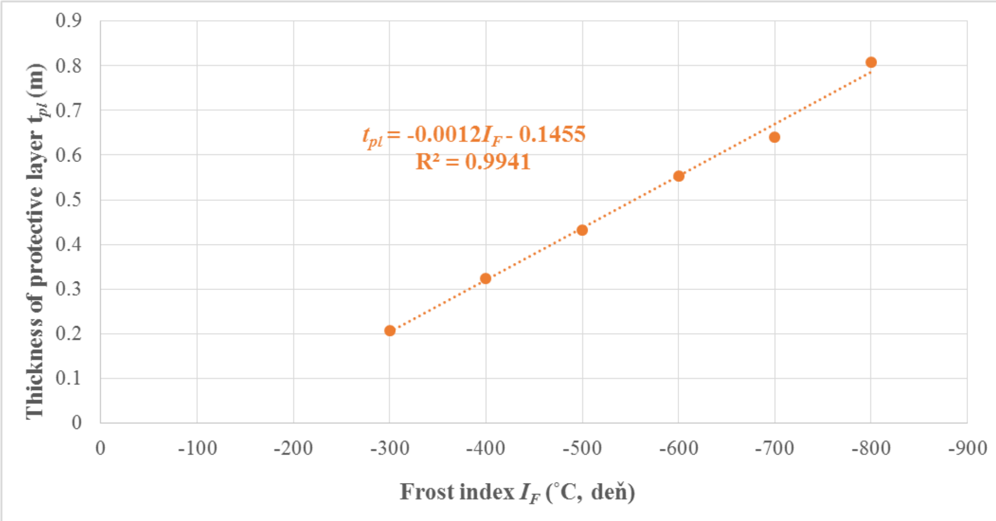

Fig. 6. Updated nomogram for the design of the thickness of the protective layer of crushed aggregate

4. CONCLUSION

The primary objective of the process of designing the railway track structure is to secure a high-quality and safe roadway that will fulfill its functions over the entire lifetime. As the dimensioning methodology of the railway track for the non-traffic load was developed in the 1960s, it must be updated with respect to new knowledge, applying modern information and communication technology and software.

The researchers at the Department of Railway Engineering and Track Management have been studying the problem of the non-traffic load of the railway track since 2003 when the first railway track model in a 1:1 scale was constructed – Experimental stand DRETM I. The research conditions were significantly improved in 2012 when the Canadian software *SoilVision* [17] (*SVHeat* [18]) was purchased. Its application required determination of several input parameters affecting the track substructure freezing. However, they were not available. Due to this reason, in 2012, a new Experimental stand DRETM was constructed. This stand was able to provide numerous necessary input parameters for relevant numerical modeling of the thermal regime of the railway track.

The experimental monitoring at the DRETM stand indicated that track substructure freezing is affected, besides the frost index value, also by:

- the length and course of the frost period,
- the occurrence of several positive mean daily air temperatures in the frost period,
- the average annual air temperature (amount of heat accumulated in the track substructure during the year),
- moisture of materials built in the track structure and its subgrade (possible saturation of material generated by the capillary action of groundwater,
- snow cover thickness.

The above-mentioned factors were considered in the design of the nomogram of the track substructure dimensioning for the non-traffic load, which basically is the determination of the thickness of the protective layer of the frost-susceptible subgrade surface. In contrast to the valid design nomogram stated in [1], the output parameter is not the design of the thickness of the protective layer of gravel sand as this material is no longer applied in protective or foundation layers.

Subsequently, this nomogram update was extended to crushed aggregate and besides the air frost index value, also the average annual temperature θ_m, influence of the snow cover (*nf* factor), and the real maximum moisture that crushed aggregate material in the track substructure can reach were considered in the design of the protective layer thickness.

The research of the influence of the non-traffic load (effects of climatic factors, primarily water and frost) focuses on updating the dimensioning methodology of the track substructure for the non-traffic load. As stated in [1], if the structural thickness of the protective or foundation layer reaches greater values (over 600 mm), application of materials with better thermal insulation properties (in case of protective layer), or better deformation resistance (in case of a foundation layer) is recommended. Consequently, in the future research, it is necessary to design nomograms, i.e. determine the structural thickness of layers, for such types of application of construction materials. As stated in Part 2.1, in 2017 the Experimental stand DRETM was completed. It includes 6 measuring profiles; 3 of them include various thermal insulation materials (Liapor, Liapor concrete, Styrodur) in their substructures.

Hence, further DRETM research will focus on the collection of necessary input parameters for the numerical modeling of freezing of the track substructure (railway track) with built-in thermal insulation materials. In this way, it is possible to create prerequisites for nomograms that will enable to design relevant structures with built-in thermal insulation elements that will resist the non-traffic load of the railway track.

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