Numerical modeling of freezing of structural objects in transition zones of railways

S Hodás and A Pultznerová

University of Žilina, Faculty of Civil Engineering, Department of Railway Engineering, Univerzitná 8215/1, SK-010 26, Žilina, Slovak Republic

E-mail address: stanislav.hodas@uniza.sk

Abstract. The structure of the transition zone of the railway formation is composed of layered materials built into it, which must be resistant to adverse winter climatic conditions characteristic for the region. Among the most dangerous factors is the freezing of these materials and therefore the increased resistance to freezing in winter period is required. By this damage, change of their internal structures and material-technical characteristics can occur. For example, as a consequence of freezing, the structure may be affected by the consequent reduction of resistance of these layers to traffic load (axle loads, deformation modules of the individual layers, etc.). Special construction structures are also designed in the track and the paper is dedicated to transition zone, i.e. reinforced concrete tub as an intermediate element in changing the types of railway formation (the area between the slab track and the continuous track bed). In the experiments using the numerical models, the depth of freezing of the structural objects in the transition zones of the tracks is analyzed, i.e. the zero isotherm height position for 0 °C in the railway structure is determined and compared with respect to the bottom surface of the concrete tub as well as the FPL (frost protection layer) in the continuous track bed, subsequently the design of the objects may be modified.

1. Introduction
The transition between a slab track and a rail bed structure is one of the critical points on a railway track. In this section of a railway, a reinforced concrete tub is designed for the transition between them, which is intended to damp the dynamic effects arising from the pass of a train on this section. Within the research, the freezing of this transition zone (TZ) has been verified, i.e. the zero isotherm in the individual structural layers was monitored (curve or surface with a temperature of 0 °C). Freezing adversely affects to the materials built in the railway track and the layers above the zero isotherm must be frost resistant.

The paper describes research for climatic temperature load from frost at freezing index approx. $I_F = -600 \, ^\circ\text{C}\cdot\text{day}$ in [1], [2], using two thicknesses of protective gravel layer $h_{FPL} = 450$ mm and $h_{FPL} = 600$ mm for continuous rail bed behind the reinforced concrete tub. The $I_F$ is the sum of the negative daily temperatures during the winter period, each period begins when the first four days have minus temperatures.

Photographs of the realized construction object of the transition zone on the double-track of the main corridor line Bratislava – Žilina in Slovakia for the speed $V = 160 \, \text{km/h}$ are shown in figure 1.

Numerical modeling is beneficial for designers and achieves qualified results. Modeling of the transition zone TZ is realized by the Finite Element Method calculation [3].
2. Model of transition zone and climatic load
The numerical model must exactly correspond with the designed structure of the reinforced concrete tub and to the design of the track formation before and after this object (slab track and continuous track bed). The material-technical characteristics of structural layers verified in laboratory tests or standard characteristics are entered to the model.

An important element is the initial setting of the initial temperatures in the particular structural parts of the TZ model and the track (also in the substructure). Numerical models of the transition zones are loaded by the climate regime in a 120 day freezing period with freezing index of $I_F = -600 \degree C \cdot day$ (winter freezing period), which is characterized by mean daily air temperatures $T_m$. 

![Figure 1. Transition zone on double track $V = 160 \text{ km/h}$.

![Figure 2. Climatic load: (a) mean daytime temperatures $T_m$ and (b) snow load $h_{snow}$.](image)
(average measured 4 times over 24 hours). These railway track models were frost-loaded for 4 months, i.e. in the winter period from November to March of the consecutive year (in Central Europe approx. 15.11. - 15.03.), according to figure 2a. During this research, a frosty winter period with several freezing periods for the climate load of the model was searched, from a practical point of view, the period with \( I_F = -600 \, ^\circ C \cdot \text{day} \) (town of Poprad in the High Tatras region) was selected.

Input technical characteristics of structural materials of particular layers of the railway track models in these experiments for the transition zone are considered according to table 1 [3] where the values are for thermal conductivity – \( \lambda \), soil dry density – \( \rho \), specific heat capacity – \( c \) and material humidity – \( w \).

| Material            | \( \lambda \) J/(day\cdot m\cdot C) | \( \lambda / (24\times60\times60) \) W/(m\cdot K) | \( \rho \) kg/m\(^3\) | \( c \) J/(kg\cdot C) | \( w \) % |
|---------------------|-------------------------------------|-----------------------------------------------|----------------|----------------|-------|
| Railway ballast     | 60000                               | 0.69                                          | 1908           | 980            | 2     |
| Reinforced concrete | 136000                              | 1.57                                          | 2400           | 1020           | 2     |
| Subgrade            | 130000                              | 1.50                                          | 2081           | 1585           | 17    |
| Subsoil             | 105000                              | 1.22                                          | 1646           | 1495           | 18    |

3. Numerical modeling of structural object freezing

The primary task is the preparation of a numerical model (design of a new or already existing transition zone of the track as part of testing). Numerical models for single and double track were created in research experiments. The paper and the figures show the model of the double-track of the main corridor line with the purpose of continuous presentation (calculations were done on both and their results are shown in table 2 to table 7).

The model must be created in 3D Environment Models, as it is done in our research using [3], in order the temperature transfer occurred throughout the 3D spatial model. In case of a railway track without objects, analysis of the characteristic cross-sections in 2D is sufficient (the longitudinal axis behaves in the same way). However, the transition zone is a complete three-dimensional structural object with spatial blocks, and therefore processing as a 3D model is advantageous as the frost penetrates all parts of the structural object in the XYZ space.

![Figure 3. Numerical model of the structural object TZ: (a) definition of the surfaces and (b) 3D parts.](image-url)
The numerical model of the transition zone with the design of particular spatial blocks and structural layers is shown in figure 3 (half of the length of the object was used for the calculation), where the finite element calculation network layout is also used. The length of the transition zone (the concrete tub is half of the length of the structure, but the model includes only for the first 10 m of the structure) is \( l_{TZ} = V/2 \) (m/s), for example, for the velocity on the railway corridor \( V = 160 \) km/h the length of the object is \( d_{TZ} = 22.22 \) m.

The design of the structural object of the transition zone is a complex issuer. In these cases, preparation for calculation of temperatures that are dependent on external influences is necessary, i.e. how the model was exposed to the freezing climatic exterior environment (the top surfaces in figure 3 that are affected by the climatic load). All surfaces and edges of 3D objects that make up the entire structural object must be defined.

3.1. *Evaluation of freezing in the longitudinal sections YZ*

This section is a longitudinal section of the structural element in 3D, as shown in figure 4a at \( X = +2.10 \) m, which is shown in the section in the track axis of a double-track line. A detailed graphical evaluation is shown in figure 4b (numerically is referred in the model databases) where the freezing of the zero isotherm for the 120th day of the experiment (maximum values) is marked. The displayed objects are dark, as the finite element net is dense, for color details it is necessary to use its close-up zoom to enlarge the profile. The particular temperature values are also color-coded in the legend.

![Figure 4. Temperature course in the YZ axis – 120th day of modeling: (a) 3D transition zone and (b) detail of longitudinal section.](image-url)
The longitudinal section along the track axis with the temperature transition through the structure shows the parts where the reinforced concrete threshold of the tub (stationing 0.00 to 2.00 m) is located, the iron-concrete tub with rail bed (stationing 2.00 to 22.00 m) and two different railway formations (before stationing 0.00 a fixed track is built and after stationing 22.00 m is a continuous rail bed).

3.2. Evaluation of freezing in the longitudinal sections XZ

Sections XZ of the numerical model show the temperature transition and the zero isotherm in cross-sections, this is the most effective view of this graphical evaluation of the calculation results (figure 5 and figure 6). When interpreting the graphical results, it is evident that the zero isotherm is found at the depth $h_{F2}$ in table 2 and table 3 in the track axis for the 120th day of the numerical experiment. In figure 5b it is shown for stationing $Y = +6.00$ m, the result values are presented in table 2 and a section through the concrete threshold $Y = +1.00$ m is shown in figure 6.

**Figure 5.** Temperature course XZ – 120th day of modeling: (a) 3D transition zone and (b) cross-section of the tub with railway bed.

**Figure 6.** Temperature course XZ: cross-section of the reinforced concrete threshold.
The structural object can also be cut in the horizontal XY direction, for example in the longitudinal walls of the concrete tub, but the most important are the XZ cross sections.

The graphical and numerical results of the numerical model of the transition structure are processed in 60-minute intervals (or 30 minutes); 3D (or 2D) animation for each particular processing and model recalculation has been created.

4. Discussion – final evaluation of the experiments

Result values of the freezing experiment of the transition zone show that at the freezing index \( I_F = -600 \, ^\circ\text{C} \cdot \text{day} \) (figure 5, table 2 and table 3) in the part of the concrete tub only with a railway bed, freezing under the concrete tub in the track axis does not occur (see cross section in \( Y = +6.00 \, \text{m} \) and longitudinal track section in \( X = \pm 2.10 \, \text{m} \)). Freezing in a part of the reinforced concrete threshold approached to the permissible limit of \(-0.95 \, \text{m}\) at the bottom of this threshold. However, below the marginal rail (L or R), the zero isotherm already exceeds this limit and interferes into one structural layer of the embankment, i.e. under the transitional reinforced concrete tub. Either it is necessary to design a new protective gravel sand layer FPL (as in the continuous track bed), or we will consider the structural layer partially frosty, but increased number of repairs and interventions in the geometry of track axes during track operation in the transition zone will be expected. The above applies to snow thickness \( h_{\text{snow}} = 10 \) to 20 cm at temperature conversion factor \( n_F = 0.85 \). For the marginal rails of both tracks of the double-track line (or both single-track rails L – left and R – right), there is also a tendency of freezing in the direction from the side slope as well as the margins of the reinforced concrete tub (figure 5, table 2).

| Stationing/cross sections (m) | \( h_F \) (m) | railway axis | R – rail |
|-----------------------------|---------------|--------------|---------|
| L – rail                    |               |              |         |
| 1.00                        | -1.10 \( \times \) | -0.97 \( \checkmark \times \) | -0.93 \( \checkmark \) |
| 6.00                        | -0.80 \( \checkmark \) | -0.62 \( \checkmark \) | -0.55 \( \checkmark \) |
| Bottom surface of the tub   | -0.95         | -0.95        | -0.95   |

Table 2. Depth of freezing \( h_F \) – cross sections XZ.

| Stationing (m) | \( h_F \) (m) | railway axis |
|----------------|---------------|--------------|
| 0.00           | -0.95 \( \checkmark \) |             |
| 1.00           | -0.96 \( \checkmark \times \) |             |
| 6.00           | -0.64 \( \checkmark \)   |             |
| 10.00 (detto 22.00) | -0.64 \( \checkmark \) |             |
| Bottom surface of the tub | -0.95 | |

Table 3. Depth of freezing \( h_F \) – longitudinal profile YZ (track axis \( X = \pm 2.10 \, \text{m} \)).

To supplement the data, experiments will also be described on the railway track with a continuous track bed for double-track and single-track track within freezing for the type of railway formation in the embankment with FPL with the protective layer with its thicknesses of \( h_{\text{FPL}} = 450 \, \text{mm} \) and \( h_{\text{FPL}} = 600 \, \text{mm} \). The double-track freezes to depths according to the zero isotherm in table 4 and table 5, the climatic load is the same as in the transition zone at the freezing index \( I_F = -600 \, ^\circ\text{C} \cdot \text{day} \) and the detailed division is 0.00 to 0.30 m depending on the snow thickness. At \( h_{\text{snow}} = 0.00 \, \text{m} \) we are talking
about hard frost without snow cover with considerable freezing of layers; this is low probable situation. From a practical point of view, 0.10 to 0.20 m of snow is considered (the trains adjust the height of the running track by their own run), snow is considered an excellent thermal insulator.

Table 4. Depth of freezing \( h_F \) – railway bed (double track).

| Track/conditions | \( h_F (m) \) | railway axis | R – rail |
|------------------|----------------|--------------|---------|
| Double track \( h_{FPL} = 450 \) (mm) | | | |
| \( I_F = -600 \) (°C∙day) | -1.46 × | -1.25 × | -1.23 × |
| \( n_F = 0.85 \) | -1.08 ✓ | -0.78 ✓ | -0.70 ✓ |
| Bottom surface (FPL) | -1.15 | -1.08 | -1.01 |
| Double track \( h_{FPL} = 600 \) (mm) | | | |
| \( I_F = -600 \) (°C∙day) | -1.52 × | -1.35 × | -1.25 × |
| \( n_F = 0.85 \) | -1.12 ✓ | -0.89 ✓ | -0.76 ✓ |
| Bottom surface (FPL) | -1.28 | -1.21 | -1.14 |

Zero isotherm depths are investigated in the track axis and below particular track rails (L – left and R – right); pay attention to the different transverse slope of the lower surface of the FPL protective layer.

Another experiment of the numerical modeling was also solved on a single track (results are shown in table 6 and table 7). During the experiments it was found that the accumulated heat in the double-track railway body from the previous period (summer, autumn) is higher, because in the railway formation there is a larger volume of material [5], [6] and there is also somewhat less freezing depths that show table 4 to table 7 (values need to be compared only for the same thickness of \( h_{FPL} \) used). The values in the tables marked ✓ are within the limit and the values × exceed it; the required limit is the lower surface of the transition zone or protective layer (the last rows in the tables) to protect the other layers from frost destruction [7] and [8].

Table 5. Depth of freezing \( h_F \)– railway bed (single-track).

| Track/conditions | \( h_F (m) \) | railway axis | R – rail |
|------------------|----------------|--------------|---------|
| Single-track \( h_{FPL} = 450 \) (mm) | | | |
| \( I_F = -600 \) (°C∙day) | -1.47 × | -1.34 × | | detto L=R |
| \( n_F = 0.85 \) | -1.20 × | -1.12 × | |
| Bottom surface (FPL) | -1.06 | -1.00 | -1.06 |
| Single-track \( h_{FPL} = 600 \) (mm) | | | |
| \( I_F = -600 \) (°C∙day) | -1.64 × | -1.59 × | | detto L=R |
| \( n_F = 0.85 \) | -1.28 × | -1.22 × | |
| Bottom surface (FPL) | -1.22 | -1.15 | -1.22 |
5. Conclusions
Civil engineers design various structural objects and their structures must meet different criteria required by standards. The railway formation, in our case the construction of transition zones (structure of a reinforced concrete tub with a rail bed), must comply with the transmission of dynamic loads (various shocks and vibrations frequencies), transmission of the load from the railway wheel to the particular structural layers (deformation modules) and it must not be forgotten of the resistance to frost penetration into the parts of this structure [9] and [1].

Repeated freezing of the structural elements under freezing climatic conditions (even several freezing periods during one winter) may disturb the material structure and reduce other structural features, such as the abovementioned load-bearing capacity, i.e. reduced modulus of deformation (different module standard values for individual structural layers). Thereafter, repeated maintenance of the spatial geometry of the track axis on the objects and its adjacent parts will be increased.

During experiments – numerical [7] and [5], but also on models in [10] and [11], the greatest depth of freezing is proved in the threshold area of the transition zone where the reinforcing concrete block is located. Here it seems necessary to design a protective layer of FPL. In the part of the concrete tub, where there is also a gravel railway bed, the structure is sufficient for the depth of freezing. The FPL layer should be with higher height at the outer rail (higher freezing from the side of the railway formation), for example, the design of the roof transverse slope of the lower surface of the FPL 4 to 5 %.

Similarly as it is for the track with a continuous railway bed behind the transmission zone.

From the results of modelling track with only continuous track bed and FPL protective layer with the snow layer $h_{snow} = 0.10$ to 0.30 m it satisfies for double track until the snow layer falls below 0.10 m. At a snow thickness of 0.00 m, frost enters the structure clearly because there is no snow, which is a good thermal insulator (it would be a freezing winter without a snow cover).

The single track with the same conditions as previous experiments is worse. The design at the freezing index $I_F = -600 \, \degree C \cdot \text{day}$ does not satisfy even with 0.10 m of snow. The experiments have clearly shown that the larger volume of material in the railway formation is more resistant to frost; the formation has more accumulated heat from the previous period. The double track is better from this point of view (solved with higher embankment, [6].

From this point of view, the initial temperatures in the layers and railway substructure are also important at the beginning of the experiments (on day 0), where temperatures of 10 to 15 °C in the particular layers of the structure were considered (from examination of real models of the [11]). But if the temperature of winter starts for example [10] at a level of approx. 6 to 10 °C, mentioned zero isotherm depths will be deeper by approx. 4 to 8 cm at this freezing index on realized models of research made in previous years at the Department of Railway Engineering, Faculty of Civil Engineering, University of Žilina by authors [1], [11] and [6].

Finally, we can conclude, that building of the real models at the scale 1:1 has made possible to verify numerical modelling versus the true value of these models, and so in recent years, numerical models have been tested without laborious and costly constructions of models.

Acknowledgments
The presented parts of the paper were created within the framework of the research activities VEGA 1/0084/20 [4] by the Department of Railway Engineering at the Faculty of Civil Engineering of University of Žilina (DRE-PCE-UNIZA).

References
[1] Ižvolt L, Dobeš P and Hodás S 2018 Impact of the method of rail track routing on the thermal regime of subgrade structure - numerical modelling of non-traffic load, Int. J. of Transport Development and Integration 2 (3) pp 250-7
[2] Hodás S, Ižvolt L and Dobeš P 2016 Preliminary results and conclusions from mathematical modelling of thermal regime of railway track structure, Int. J. of Computational Methods and Experimental Measurements 4 (2) pp 69-79
[3] SV-HEAT 2D/3D 2020 Finite element - freeze/thaw modeling, FlexPDE, SVOFFICE - Geotechnical modeling suite, SVOFFICE™5/GE and SV-HEAT™GE, (SoilVision systems Ltd Canada)

[4] Numerical and experimental analysis of transition zones of objects of structures of railway superstructures and objects of formation substructure 2020 Scientific research (Dept. of Railway Engineering Faculty of Civil Engineering University of Žilina Slovakia)

[5] Hodás S and Pultznerová A 2017 Modelling of railway track temperature regime with real heat-technical values for different climatic characteristics. Civil and Environmental Eng. Sci. Technical J. 13 (2) pp 134-42

[6] Hodás S and Pultznerová A 2019 Freezing of the subballast layers of the railway formation – high embankment and double track. Civil and Environmental Engineering Scientific Technical J. 15 (1) pp 5-12

[7] Chen Ch and McDowell G R 2014 An investigation of the dynamic behaviour of track transition zones using discrete element modelling Proc. of the Institution of Mechanical Engineers, Part F: J.of Rail and Rapid Transit 230 (1) pp 117-128

[8] Zuada Coelho B and Hicks M A 2016 Numerical analysis of railway transition zones in soft soil. Proc. of the Institution of Mech. Engineers, Part F: J. of Rail and Rapid Transit 230 (6) pp 1601-13

[9] Wang H, Markine V and Liu X 2018 Experimental analysis of railway track settlement in transition zones. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 232 (6) pp 1774-89

[10] Heydari-Noghabi H, Zakeri J A and Esmaeili M 2018 Field study using additional rails and an approach slab as a transition zone from slab track to the ballasted track Proc. of the Institution of Mech. Engineers, Part F: J. of Rail and Rapid Transit 232 (4) pp 970-8

[11] Hodás S and Ižvolt L 2014 Modeling of temperature regime of railway track structure and its comparison with the results of experimental measurements COMPRAIL XIV Railway engineering design and optimization, Rome, Italy, Edited by C.A. Brebbia, WESSEX Institute of Technology, WitPress, Southampton United Kingdom 14 pp 253-65