Influence of Frost Protective Layers on the Realisation of the Track Bed Structure

Janka Sestakova 1, Peter Dobes 1

1 University of Zilina, Faculty of Civil Engineering, Department of Railway Engineering and Track Management, Univerzitna 8215/1, Zilina, Slovak Republic

E-mail: janka.sestakova@fstav.uniza.sk

Abstract. The railway track is a structure built of structural elements and materials with different material and geometrical properties. The design, construction, management and operation of the structure are governed by the standardized requirements of the railway infrastructure manager. The priority aspect of long-term serviceability is the resistance of the rail grid and the track bed to the stress. In terms of the railway body, the load is represented by the traffic and non-traffic load. The paper analyses various reference types of the track bed, (designed and assessed according to currently valid standards) and design types (designed, assessed and tested within the research of the Department of Railway Engineering and Track Management of the University of Žilina). Based on the parameters of the material and constructive structure, a matrix of activities of time plans for building reference and design models is created. This matrix also enabled to develop visualizations of standard links among construction activities.

1. Introduction
The railway track design (figure 1) resists the traffic and non-traffic loads by its material properties and the interaction of structural elements (resistors) against force effects. The condition of the structure is affected by the current track layout and track geometry, railway superstructure system, structure of the railway substructure, the type and intensity of railway operation, condition and speed of the railway vehicles, and the quality of repair work of the railway superstructure and substructure.

One of the key indicators of the initial quality of structure is adherence to the parameters of the track bed project during construction. The prescribed resistance of the structure to the traffic and non-traffic loads (climatic factors) is ensured by the design of standardized track bed types for particular input conditions [1]. Within the framework of the research of the Department of Railway Engineering and Track Management of the Faculty of Civil Engineering of the University of Žilina, new structures with frost protective layers were designed and tested in field conditions to protect the soil of the subgrade surface against undesirable effects of frost. Building protective layers affects the connections among track bed construction activities.
2. Load on the railway track structure and its response

The traffic load, resulting from the interaction of the rail vehicles and the track, has the highest impact on rails or load-bearing structural elements in the turnout, whose load-bearing capacity determines the load-bearing capacity of the entire railway superstructure of track or turnouts. The rail is directly (centrally or eccentrically) loaded with vertical wheel forces, horizontal (guide) forces transverse to the track axis, and wheel forces parallel to the track axis. Vertical and horizontal transverse forces produce a bending moment in the rail. The rail is also loaded by normal forces caused mainly by changes in rail temperature in the continuously welded rail.

The effects of the operational load are not solely limited by the application of a force load on the railway track. The quality of the structure is affected by the wear and tear of the rolling stock or inaccurate handling of the transported commodities. The repair work can also directly contribute to the load of the structure, namely by the vertical wheel and transverse guide forces and the use of the structure for transport and operation. Some repair work produces an increased level of vibration (tamping, compaction, dynamic stabilisation) or can affect changes in internal forces in a continuously welded rail or adversely affects the quality of material and geometrical parameters of the structure and its parts. The weather influences the behaviour of the track design, in particular by the effects of low and high temperatures to all elements of the structure. The track load in the longitudinal direction is affected by changes in temperature of rails, which tend to extend or shorten. Other climatic influences (wind and precipitation) cause material and geometric changes in structural elements and, in specific cases, contribute to the track load in vertical and transverse directions.

The structural wear, caused by the traffic and non-traffic loads, is transferred to the ballast bed and other track bed layers or onto the support slabs (hydraulic bounded layer) of the ballastless track structure through the rails, fastening elements and rail supports and initiates the response of the entire structure and its individual components. In order to determine the quality of deterioration or damage to the railway, it is important to identify the load acting on it and the track response to the load.

A poorly resistant or insufficiently protected track bed reacts to the effects of traffic and non-traffic load by deterioration, represented by errors due to insufficient deformation resistance of the subgrade surface, formation protective layer and/or ballast bed, or track bed freezing. The decisive factors influencing the occurrence of freezing errors are frost, structure and moisture of the structural layer material. Errors caused by the track bed freezing are manifested by changes in the track layout and track
geometry, excessive moistening of the subgrade surface, reduction of its deformation resistance and the consequence of traffic load and permanent track deformations [2].

3. Track bed characteristics
The structural layers of the track bed are laid between the rail support surface and the subgrade surface. The material and geometrical properties of the layers ensure the transfer of the effects of traffic and non-traffic loads on the subgrade surface, increase the track bed stability and improve the water and temperature regime of the track bed.

The structural layer under the rail bed is called the formation protective layer. The main features of this layer are:

- the distribution of the effects of the traffic load,
- protection of the subgrade surface against the effects of water and frost,
- prevention of the penetration of the ballast bed material into the subgrade surface. [1]

The protective layer is built in the track bed to protect the subgrade surface against adverse effects of frost, weathering or mechanical damage. It has a filtering and drainage function in the track bed structure. An alternative to the aggregate layer is thermal insulation elements in the form of prefabricated slabs or bound or unbound layers of material (figure 2).

![Figure 2. Structural layers of the track bed](image)

In the track bed design and assessment, the design parameters of the deformation resistance (bearing capacity) of the subgrade surface and the sub-ballast surface are respected in the calculation models. The assessment parameter of the deformation resistance is the static modulus of deformation. The required (minimum) value of the static deformation modulus is dependent on the railway track speed zone (SZ) (table 1) [1].
Table 1. Required values of static deformation modulus at the subgrade, or at the formation (created by [1])

| Speed zone | Speed V (km/h) | Required static deformation modulus at the subgrade $E_0$ (MPa) | Required static deformation modulus at the formation $E_s$ (MPa) |
|------------|----------------|---------------------------------------------------------------|---------------------------------------------------------------|
|            |                | new structure | existing structure | new structure | existing structure |
| $SZ_1$     | $V \leq 60$    | $\geq 15$     |                  | $\geq 30$     |
| $SZ_2$     | $60 < V \leq 80$ | $\geq 20$     | $\geq 15$     | $\geq 40$     | $\geq 30$     |
| $SZ_3$     | $80 < V \leq 120$ | $\geq 30$     | $\geq 20$     | $\geq 50$     | $\geq 30$     |
| $SZ_4$     | $120 < V \leq 160$ | $\geq 40$     | $\geq 30$     | $\geq 80$     | $\geq 50$     |
| $SZ_5$     | $160 < V \leq 200$ | $\geq 50$     |                  | $\geq 100$    |

The track bed design with regard to frost protection determines the required thickness of the sandy gravel formation protective layer under the ballast bed layer, assuming a thickness of 300 mm measured under the bearing surface of the sleeper. The sandy gravel layer and the ballast bed have the function of protecting the subgrade surface against unfavourable effects of frost. The design is satisfactory if the permissible freezing thickness of the subgrade surface soil is not exceeded, according to table 2. The sandy gravel layer may be replaced by a layer of other material having better thermal insulation properties. The thickness of such a layer is determined from the condition of equality of thermal resistance of the sandy gravel layer and the layer designed from another more effective thermal insulating material [1].

Table 2. Allowed thicknesses of the subgrade frost penetration (created by [1])

| Speed zone | Speed V (km/h) | Perilously frost active soils | Frost active soils |
|------------|----------------|-------------------------------|-------------------|
|            |                | Pericoloury frost active soils | Favourable water regime | Unfavourable water regime | Favourable water regime | Unfavourable water regime |
| $SZ_1$     | $V \leq 60$   | 0.50                          | 0.30              | 0.70                      | 0.50                      |
| $SZ_2$     | $60 < V \leq 80$ | 0.40                         | 0.15              | 0.60                      | 0.40                      |
| $SZ_3$     | $80 < V \leq 120$ | 0.30*                        | 0.00*             | 0.50*                     | 0.30*                     |
| $SZ_4$     | $120 < V \leq 160$ |                |                  |                           |                           |
| $SZ_5$     | $160 < V \leq 200$ |                |                  |                           |                           |

* It also applies to modernised railway tracks included in $SZ_3$.

4. Reference and design track bed models

In the design of the model structure building (time plan of construction work), the key information is the information about the structure and the parameters of the existing and new structure of the railway substructure and superstructure. In order to define the parameters and visualize the differences in the implementation of the railway track structure, three design track bed models ($N.1$, $N.2$, $N.3$) with a protective layer of the subgrade surface against the effects of frost have been created for four track bed reference models ($R.1A$, $R.1B$, $R.2A$ and $R.2B$):
- $R.1A$: type 3 structure with non-reinforced unbound formation protective layer and geosynthetics,
- $R.1B$: type 3 structure with reinforced unbound formation protective layer and geosynthetics,
- $R.2A$: type 6 structure with non-reinforced unbound formation protective layer and improved soil layer of local material,
- $R.2B$: type 6 structure with non-reinforced unbound formation protective layer and improved soil layer made of transported material,
- $N.1$: structure with non-reinforced unbound formation protective layer and a protective layer of extruded polystyrene slabs,
- $N.2$: structure with non-reinforced unbound formation protective layer and foamed concrete slabs
protective layer,
- \textit{N.3}: structure with non-reinforced, unbound foundation layer and a protective layer of foamed concrete prepared on site.

The material and geometrical characteristics of the structural layers of the individual models shown in figure 3 are designed for a track included in the \textit{SZ4} (120 km/h < \(V\) \leq 160 km/h). The frost design index \(I_{FD} = 700 \, ^{\circ}\)C.day is used to assess the resistance of the models to the non-traffic load. The soil of the subgrade is dangerously frosty and the water regime in the structure is unfavourable. These input conditions determine the calculated depth of freezing value of the structure at \(D_F = 1.19 \, m\).

![Figure 3. Material and geometrical characteristics of structural layers in every model (a – \(R.1A\), b – \(R.1B\), c – \(R.2A\), \(R.2B\), d – \(N.1\), e – \(N.2\), f – \(N.3\))](image)

The structures meet the demands for new construction in \textit{SZ4} according to table 1 and table 2 (highlighted in grey). The properties of the design models were experimentally verified in the framework of the research tasks of the Faculty of Civil Engineering of the University of Žilina, namely the parameters of deformation resistance on the sub-ballast surface and the depth of freezing [3 - 7].
5. Differences in the implementation of the track bed reference and design models

The following sequence of operations is followed in the construction process and its time plan:

1. spatial location of the site,
2. selection of the method of construction work,
3. data and characteristics of the old and new railway structure;
4. list of work activities (figure 4) and specification of the technological and time sequence (figure 5 and figure 6),
5. determination of the extent of construction work (quantity of material, number of structural elements),
6. selection of the type and number of mechanisms according to the list of construction technology activities,
7. calculation of the duration of individual construction technology activities,
8. calculation of the total duration of construction work and its comparison with the allowed time,
9. repair in points 4, 6 and 7 to meet the condition in point 8,
10. written and graphical schedule of work.

The matrix of construction or reconstruction time plans of the railway track (figure 4) indicates that the technology of construction of the individual models differs in the part of the track bed (activities 2-01 to 2-26). To compare the structure of the track bed construction activities of the reference and design models, visualizations of the standard links among the construction activities are created (figure 5 and figure 6). Visualizations confirm the increase in the number of design model activities compared to relevant reference models due to:

- building of a stabilized/improved soil layer of the subgrade surface and a frost protective layer of prefabricated extruded polystyrene slabs including the required technological breaks in the N.1 model compared to R.2A, R.2B,
- building of frost protective layer of prefabricated foam concrete slabs in model N.2 versus R.1A,
- building of a frost protective layer of foam concrete built on the site, including the required technological breaks in the N.3 model compared to R.1A, R.1B.

In models N.1 and N.2, the frost protective elements (prefabricated slabs) are manufactured in advance – outside the construction or reconstruction site of the railway track.

The structure of the construction activities of the individual models respects the technological requirements of the sequence of the activity start time ($S_{n,m}$) and the end of the previous activity ($F_{n,m-1}$), either with no overlap ($S_{n-m} \geq F_{n,m-1}$) or activity overlap ($S_{n-m} < F_{n,m-1}$).

6. Conclusion

The resistance of the structure of the railway track to the effects of the non-traffic load in the track bed area and the track skeleton is ensured by the use of structural and protective layer materials with suitable thermal insulation properties. At the same time, the structure meets the priority function of resistance: resistance against traffic loads. The objective of reducing the cost of the track construction or reconstruction aims to reduce the thickness of individual structural layers and to use new unconventional materials with the required resistance to the effects of operation and weather. The presence of layers built up in contact with the subgrade surface, serving for its frost protection, influences the scheme of activities of the technology of the track bed construction and reconstruction. By assigning the activities to the reference and design models studied in the matrix of build technology activities, the differences in the construction process of the individual models were determined depending on the new track bed structure. The result of the analysis of relations in the activity matrix is the definition of the structure of activities in individual technological procedures and their visualization, which can be used in the time planning tools for the track bed structure.
### Figure 4. Matrix of activities of building time plans for reference and design models

| building-technology activities (made in track) | R.1A | R.1B | R.2A | R.2B | M1 | M2 | M3 |
|-----------------------------------------------|------|------|------|------|----|----|----|
| 1-01.1 cutting of old rails                   | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-01.2 flame-cutting of rails                 | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-01.3 removal of fish-plates                 | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-02.1 mining and loading of old track skeleton | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-02.2 track panels                           | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-03 transport of old track skeleton          | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-04 mining and loading of old ballast bed material | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-05 transport of old ballast bed material    | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-06 mining and loading of old formation protective layer material | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 1-07 transport of old formation protective layer material | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-01 alignment and compaction of subgrade     | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-02.1 transport and dumping of material      | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-02.2 stabilizer                             | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-02.3 soil                                  | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-03.1 binder                                | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-03.2 stabilizer                            | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-03.3 soil                                  | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-04 transport and dumping of new soil with an improved characteristic – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-05 spreading of new soil with an improved characteristic – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-06 compaction of new soil with an improved characteristic – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-07 care for improved subgrade              | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-08 transport and dumping of new compensation layer material | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-09 spreading of new compensation layer     | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-10 compaction of new compensation layer    | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-11.1 transport of slabs                    | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-11.2 extruded polystyrene                  | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-12.1 foam concrete                         | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-12.2 extruded polystyrene                  | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-13 transport of foam concrete formwork     | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-14 assembly of foam concrete formwork      | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-15 transportation of material and building of foam concrete layer | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-16 care for foam concrete                  | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-17 removal of foam concrete formwork       | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-18 cutting dilatation in foam concrete     | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-19 transport of geosynthetics with separation function | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-20 spreading of geosynthetics with separation function | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-21 transport of geosynthetics with reinforcement function 1. | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-22 spreading of geosynthetics with reinforcement function 1. | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-23 transport and dumping of new formation protective layer material – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-24 spreading and compaction of new formation protective layer material – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-25 transport of geosynthetics with reinforcement function 2. | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 2-26 spreading of geosynthetics with reinforcement function 2. | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-01 transport and dumping of the new formation protective layer material – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-02 spreading of the new formation protective layer material – by layers | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-03 transport and dumping of the new ballast bed material – bottom layer | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-04 spreading and compaction of the new ballast bed material – bottom layer | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-05 transport of new ballast bed material   | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-06.1 track panels                          | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-06.2 singly                                | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-07 installing od fish-plates               | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-08 transport and dumping of new ballast bed material – top layer | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-09 tamping and levelling – 1.              | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-10 ballast regulating – 1.                | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-11 tamping and levelling – 2.              | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-12 dynamic track stabilization            | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-13 ballast regulating – 2.                | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
| 3-14 installation of continuously welded rail | ✓    | ✓    | ✓    | ✓    | ✓  | ✓  | ✓  |
Figure 5. Standard links among activities of track bed structure – reference models

Figure 6. Standard links among activities of track bed structure – design models
Acknowledgment

The paper contains results of the grant project VEGA No. 1/0275/16 Structure Optimization of Track Bed Due to Non-traffic Load Aspect.

References

[1] L. Izvolt, J. Sestakova, M. Smalo, Railway Engineering 2. Diagnostics, Mechanisation and Technology of Maintenance of Railway Track. 1st ed. (in Slovak) Zilina: University of Zilina, 2015. ISBN 978-80-554-1169-9.

[2] Technical Standard of Slovak Railways 73 6312 : 2005 : Design of Structural Layers of Track Bed. (In Slovak)

[3] P. Dobes et. al. The Determination of Values of the Specific Heat Capacity of the Selected Thermal Insulation Materials Used in Track Bed Structure. In 26th R-S-P Seminar. Vol. 117. Theoretical Foundation of Civil Engineering. Warsaw, Poland, 2017. eISSN 2261-236X, p. 1-8.

[4] L. Izvolt, P. Dobes, M. Pitonak, Preliminary Results and Conclusions from the Experimental Monitoring of Thermal Regime of Railway Track Structure. International Journal of Transport Development and Integration. 2016, 1(3), p. 529-539. ISSN 2058-8305.

[5] J. Vlcek et al. Experimental Investigation of Properties of Foam Concrete for Industrial Floors in Testing Field. IOP Conf. Ser.: Earth Environ. Sci. 95 022049. Available from: https://doi:10.1088/1755-1315/95/2/022049

[6] M. Decky et al., Foam Concrete as New Material in Road Constructions, In World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium. Vol. 161. Prague, Czech Republic, 2016. ISSN 1877-7058, p. 428-433. Available from: https://www.sciencedirect.com/science/article/pii/S1877705816327953

[7] V. Valaskova, J. Vlcek, M. Drusa, Experimental and Computational Dynamic Analysis of the Foam Concrete as a Sub-base Layer of the Pavement Structure. In 14th International Conference on Vibration Engineering and Technology of Machinery. Vol. 211. Lisbon, Portugal, 2018. eISSN 2261-236X, p. 1-6. Available from: https://www.matec-conferences.org/articles/matecconf/abs/2018/70/matecconf_vetomacxiv2018_13002/matecconf_vetomacxiv2018_13002.html