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PERMAFROST ENGINEERING

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PREVENTION OF DEGRADATION OF PERMAFROST SOILS AT THE BASE OF RAILWAY EMBANKMENTS

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The features of the interaction of the railway roadbed with the permafrost soils of the base have been considered by the example of the Salekhard–Nadym line located in the subarctic zone of the permafrost area. The causes for the permafrost degradation at the base of the roadbed have been revealed and the methods for their prevention have been proposed.

Railway, permafrost, roadbed, base, prevention of degradation

INTRODUCTION

The Northern Latitudinal Railway (hereinafter as NLR) should link the European and Asian parts of Russia in the subarctic zone. Its construction has been provided for in all strategic documents defining the development of the country's transport system for the period up to 2030, and has been approved by the orders of the Government of the Russian Federation. The section from Salekhard to Nadym 335 km long is a part of the NLR along which it is planned to carry out intensive traffic of heavy trains. A feature of the line is that it is located in the Far North.

The following natural conditions are typical for the territory along which the NLR will be laid. Long winter and freeze-up lasts up to 240 days; the low air temperatures in winter (up to −62 °C) and those in summer (up to +36 °C), the mean annual air temperature in Nadym is −5.5 °C, and that in Urengoy is −7.8 °C. The wind speed reaches 24 m/s. The volume of snow transport is 400–600 m^3/m. In addition, the duration of snowstorms in the winter season is significant, reaching 70 days. The construction area is characterized by the high density of rivers and lakes, intense swamping and icing formation. The permafrost soils with temperatures ranging from −0.2 to −1.0 °C have a continuous distribution. The snow cover formed near the roadbed has a height above the critical value, at which the permafrost thawing occurs. There are no suitable soils for the construction of the roadbed (fine and silty sands prevail). In addition, there are no labor resources in the area due to the low population density (less than 1 person per km^2).

OPERATION EXPERIENCE

In the subarctic part of permafrost zone, the company OJSC Russian Railways operates: the Inta–Chum–Labytnangi line (part of the Northern Railway) built in the 1940s, and the Surgut–Korotchayevo line (part of the Sverdlovsk Railway) built in 1970s. A characteristic feature of the roadbed of these roads is the increased deformability of the embankments in the form of uneven subsidence (Fig. 1), caused by the thawing of the frozen soils of the base, which has been continuing for a long time after the construction, leading to significant disturbances of the rail track and necessitating the frequent alignments and elevations of the track.

Due to these deformations, the safety of train traffic decreases, which leads to a significant increase in the number of restrictions on the train speed. The extent of the areas with the current subsidence deformations of the embankment in these areas is shown in Table 1.

The main reason for the deformations of the roadbed constructed on the permafrost soils at the first stage after the construction completion, as observations show, is the degradation of permafrost at the roadbed base, caused by the disruption of the natural conditions of the heat transfer between the atmosphere and the soil [*Ashpiz, 2016*]. To assess the change in the mean annual soil temperature t_ξ at the bottom of the seasonally thawing layer after the roadbed construction one can use the method of temperature corrections [*Garagulya, 1985*]:

$$t_\xi \approx t_{\text{air}} + \Delta t_R + \Delta t_{\text{sn}} + \Delta t_{\text{veg}} + \Delta t_{\text{w}} + \Delta t_\lambda + \Delta t_{\text{in}} + \Delta t_{\text{cond}} + \Delta t_{\text{conv}}, \quad (1),$$

where t_{air} is the mean annual air temperature, °C; Δt_R, Δt_{sn}, Δt_{veg}, Δt_{w}, Δt_λ, Δt_{in}, Δt_{cond}, Δt_{conv}, are the temperature corrections due to the influence of radiation, snow and vegetation cover, open water bodies, changes in thermal conductivity during freezing and thawing, infiltration of precipitation, condensation of water vapor in coarse soils and convection in the pores of water and air, respectively, °C.

As can be seen from the components of the t_ξ value (1), the construction of the embankment introduces changes in almost all components. Let us consider which of these corrections are the most important for the conditions of the subarctic zone, where the Salekhard–Nadym line is located. A feature of the subarctic regions is tundra landscape, which is characterized by strong snow transport during blizzards. At the same time, the construction of a railway embankment dramatically changes the snow deposition on its surface, increasing the thickness of snow relative to the natural conditions in the lower part of the embankment slopes and in the area adjacent to the embankment and thereby exerting a strong warming effect on the soil at the base. Field observations show that the snow height at the junction of the embankment slope with its bottom is maximum and several times higher than that height in natural conditions.

Field observations on snow cover thickness and density have been carried out by the staff of the Russian University of Transport through the slope of one of the experimental embankments located on the Obskaya–Bovanenkovo railway line (Yamal Peninsula), 314 km, hundred-meter mark (HM) 2 (2.8 m high and with a slope steepness of 1:4, Table 2). The values of the thermal resistance of the snow cover, which significantly reduce the depth of seasonal freezing of the soil, were also calculated for this section (Table 2).

Such a distribution of the snow cover along the embankment cross-section leads to degradation of the permafrost under the lower part of the embankment slopes and under the adjacent territory. The experimental confirmation of such a development of the permafrost degradation process after the construction of the roadbed has obtained by the staff of the Russian University of Transport in September 2012 during the survey of deforming embankments of the Chum–Labytnangi line. As a typical example, Fig. 2 shows the temperature field for September 2012 under an embankment with a height of 2.5 m located at 22 km of the Chum–Labytnangi line. The temperatures have been determined by means of mathematical modeling of the thermal process using the WARM software [*Patent..., 1994*]. The correctness of the modeling has been confirmed by the position of the permafrost table, established by drilling at that time (Table 3).

Similar position of the permafrost table under the embankments with a maximum thawing under the junction point of the embankment slope with the natural soil surface have been obtained on the Qinghai-Tibet Railway in China [*Xiaojuan et al., 2009*].

Fig. 1. The embankment subsidence at the section of the Chum–Labytnangi railway line.

Table 1. **Length of the railway line sections with the subsidence deformations of embankments in the subpolar part of Russia**

Parameter	Northern Railway	Sverdlovsk Railway
Length of, km		
railway track	464	318
sections with deformations	40.3	13.6
including intensive ones with speed limit	15.8	6.3
Relative length of sections with deformations, %	8.7	4.2

Table 2. **Changes in snow cover characteristics along the embankment slope at the end of winter period**

Measuring point	Thickness, m	Density, kg/m^3	Thermal resistance, (m^2·°C)/W
Top of the slope	0.31	360	0.784
Middle of the slope	0.75	470	1.515
Embankment foot	1.23	550	2.159
Field, 5 m away from the foot	0.51	420	1.167
Natural conditions	0.21	310	0.634

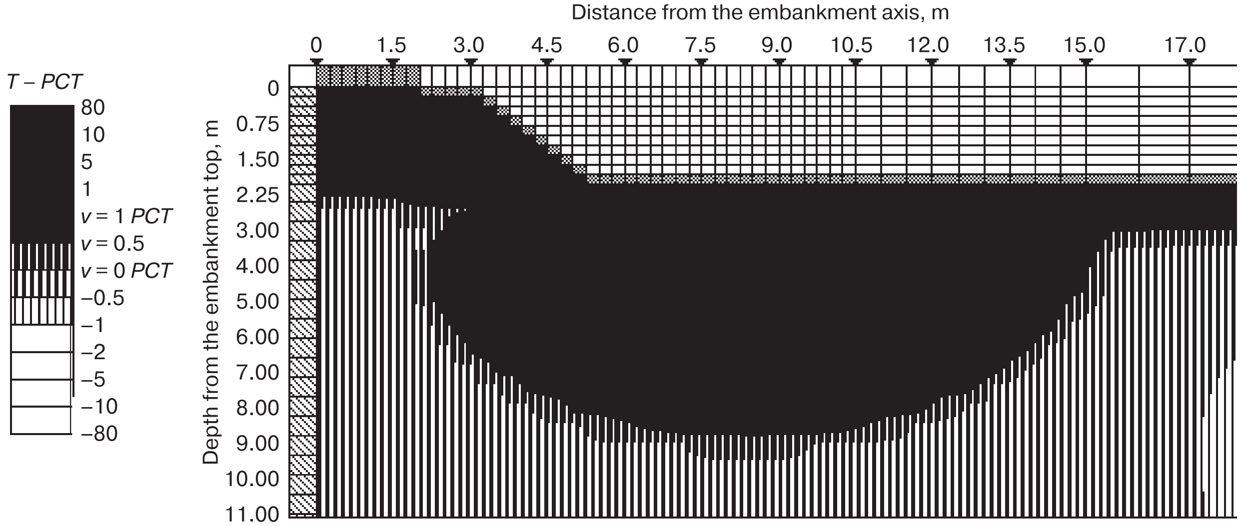

Fig. 2. The temperature field under the embankment at 22 km of the Chum–Labytnangi line for September 2012.

The center line of embankment is located on the left on the vertical axis. *T* – soil temperature, °C; *PCT* – phase change temperature, °C; *v* – the proportion of thawed soil in the block, unit fraction

Table 3. **Depth of the permafrost table in September 2012**

Depth of the permafrost table, m	Data of drilling	Data of modelling
Roadside, 2.5 m away from the track axis	5.0	6.6
Field, 9.5 m away from the track axis	5.5	6.5

Note. Depths are measured from the ground surface.

METHODS OF PERMAFROST DEGRADATION PREVENTION AT THE EMBANKMENT BASE

Many years of experience in the construction of railways have shown that neglecting the peculiarities of the thermal interaction of the roadbed with ice-rich permafrost at the base leads to serious deformations which last for a long time. For the region under consideration, the main warming factor causing the degradation of permafrost is snow accumulation (when its thickness exceeds the critical value) on the embankment slopes and adjacent parts of the natural ground surface.

By now, a positive experience has been accumulated in the design and construction of the roadbed in these conditions. A number of measures for stabilizing the roadbed have been worked out and tested in practice, the main of which, in our opinion, are the use of seasonal cooling units in conjunction with side berms and gentle embankment slopes, as well as using thermal insulation materials on embankment slopes [*Ashpiz et al., 2008; Zhang et al., 2018*].

In addition, reliable operation of the drainage system and the absence of the thermokarst depressions near the embankments (the latter, if any, should be filled up with clayey soils) are mandatory.

The exclusion of the roadbed frost heaving more than the permissible one is achieved by reducing the depth of seasonal freezing of the soils at the base using thermal insulation materials in the form of expanded polystyrene plates under the ballast prism.

We have developed the shape of embankment cross-section profiles with the heights of 3.5 m (HM 3259 + 00), 2 m (HM 2280 + 00) and 7 m (HM 2690 + 00) for the sections of the Salekhard–Nadym line located within areas with icy soils. These roadbed configuration were aimed to prevent permafrost degradation under the embankment and were calculated based on mathematical modeling of the thermal interaction of the embankment with the environment using the WARM software [*Patent..., 1994*]. In total, 14 various designs have been simulated. The observation data at the Nadym weather station have been taken as boundary conditions, as they were more unfavorable for the preservation of permafrost at the base of the railway line in comparison with those at the Salekhard weather station. The distribution of the snow cover through the embankment profile and in the adjacent territory was being determined on the basis of the observations on the Obskaya–Bovanenkovo line. The results of the option modeling with some principal design options are shown in Figures 3 and 4.

Two options have proved to be most effective in the conditions of the Salekhard–Nadym line for pre-

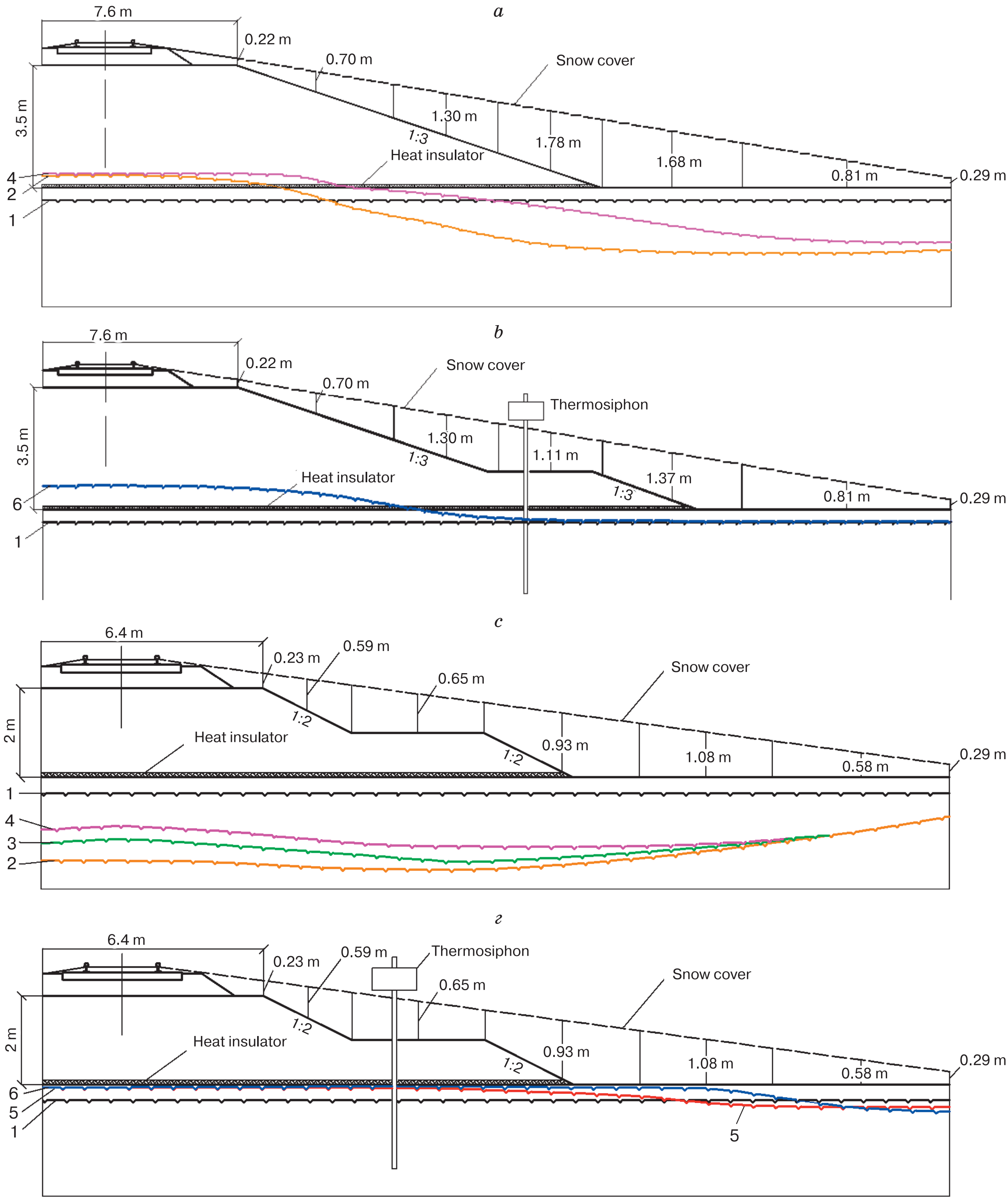

Fig. 3. Position of the permafrost table on the calculation cross-sections of the Salekhard–Nadym line:
a – HM 3259, an embankment 3.5 m high with a heat insulator at the embankment foot; *b* – HM 3259, an embankment 3.5 m high with a heat insulator at the embankment foot and with thermosiphons on the embankment berms; *c* – HM 2280, an embankment 2.0 m high with a heat insulator at the embankment foot; *d* – HM 2280, an embankment 2.0 m high with a heat insulator at the embankment foot and with thermosiphons on the embankment berms. 1 – the permafrost table in natural conditions before the construction; 2 – the permafrost table 50 years after the construction of the embankment without taking precautionary measures; 3 – the permafrost table 50 years after the construction with the thermal insulation made of expanded polystyrene plates 5 cm thick on the embankment foot; 4 – the permafrost table 50 years after the construction with the thermal insulation made of expanded polystyrene plates 10 cm thick on the embankment foot; 5 – the permafrost table 50 years after the construction with the thermal insulation made of expanded polystyrene plates 5 cm thick at the embankment foot, and with the thermosiphons on the embankment berms; 6 – the permafrost table 50 years after the construction with the thermal insulation made of expanded polystyrene plates 10 cm thick at the embankment foot and with the thermosiphons on the berms of the embankment. HM – hundred-meter mark.

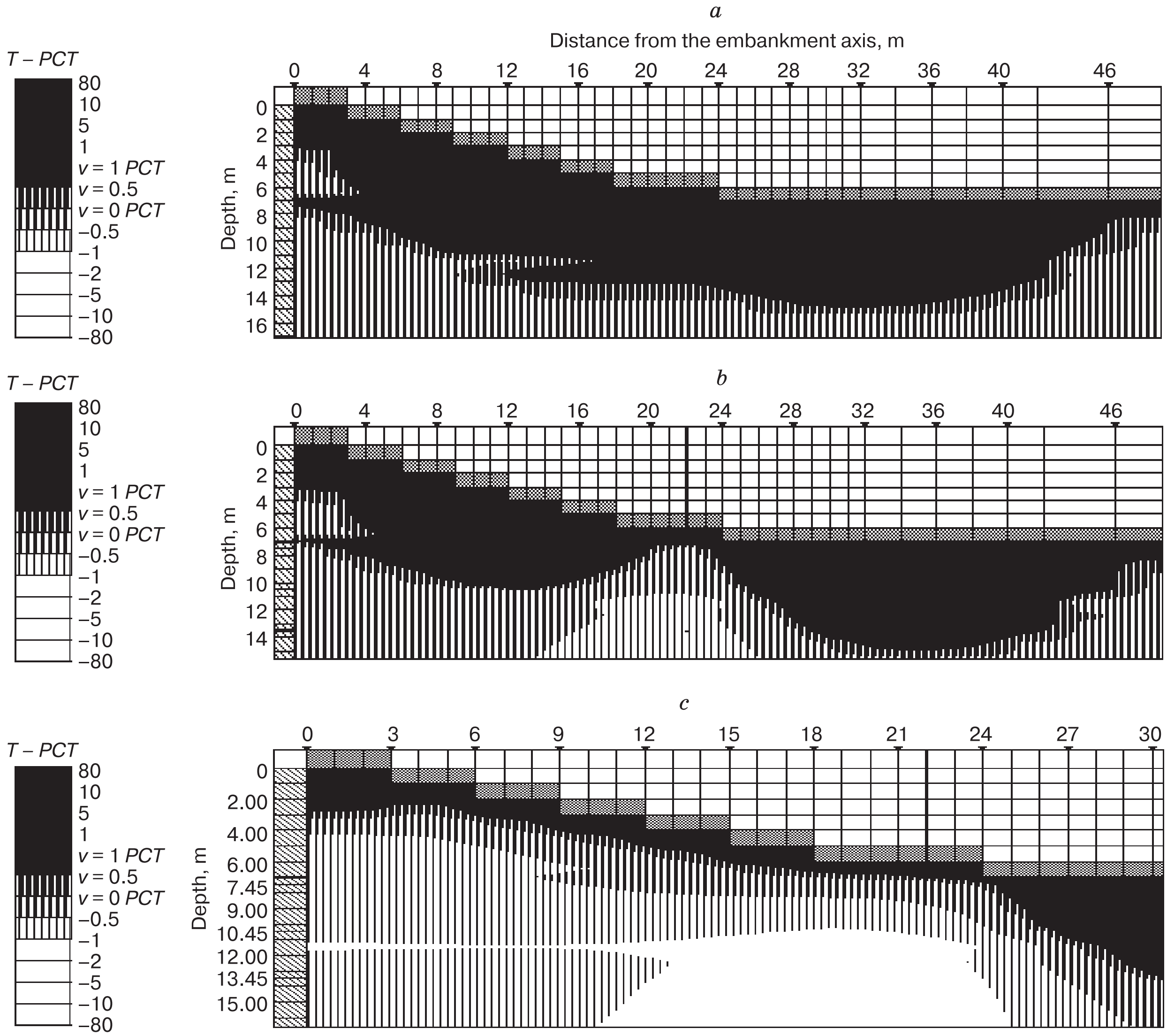

Fig. 4. Temperature fields 50 years after the construction of the embankment at HM 2690 of the Salekhard–Nadym line (an embankment 7 m high).

The temperature field in the body and base of the embankment equipped with the heat insulator made of expanded polystyrene plates: *a* – 5 cm thick at the embankment foot within the slope part; *b* – 5 cm thick at the embankment foot within the slope part and with thermosyphons on the embankment berms; *c* – 6 cm thick on the surface of slopes and berms and with the thermosyphons on the embankment berms.

venting permafrost degradation. Option 1: settling of the berms of 1.5 to 2.0 m high at the embankment base along with the installation of thermosiphons on them. Option 2: using the heat insulator at the slope, except the embankments less than 2 m high, which is less than the depth of seasonal freezing, and in these conditions it is preferable to lay the heat insulator on the embankment foot.

CONCLUSIONS

The calculations show that when the heat insulator is placed at the embankment foot and there are no thermosiphons on the berms, long-term permafrost thawing occurs at the roadbed slope and adjacent territory, which inevitably leads to thermokarst, considering the presence of soils with high ice content at the embankment base. It is possible to avoid thawing by arranging the berms and installing the thermosiphons on them along the road, and in addition, by placing a heat insulator on the embankment foot or under the slope protection. In that case, only seasonal thawing layer will occur in the body and base of the embankment, which will refreeze by the middle of winter. Within the central part seasonal thawing will affect the basement soils by no more than 20 cm deep, and in the slope part of the roadbed it will not go beyond the seasonal thawing of soils in natural conditions.

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