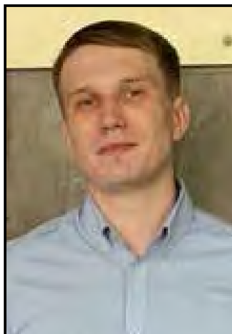
ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-1-2

World of Transport and Transportation, 2023,
Vol. 21, Iss. 1 (104), pp. 154–161

Evaluation of Influence of Seasonally Operating Cooling Devices on Thermophysical Processes of Soils of Railway Embankment Foundation

Taisia V. SHEPITKO



Igor A. ARTYUSHENKO

Taisia V. Shepitko [1],
Igor A. Artyushenko [2]
[1, 2] Russian University of Transport, Moscow, Russia.
✉ [2] *tywka351@mail.ru.*

ABSTRACT

Construction in the regions of the Far North is characterised by numerous natural barriers, the presence of permafrost soils in the foundations of structures, the lack of infrastructure and extreme natural and climatic conditions. Thus, the most urgent task both in design and construction, and in further operation of transport infrastructure in the Arctic regions is to ensure reliability of the foundation of the structure.

To ensure reliability of structures designed on permafrost soils, it is necessary to carry out thermophysical calculations and make forecasts of the influence of temperature processes on the foundation soils.

The territory of the permafrost soils (PFS) occupies a large part of Russia, therefore, expanding the possibilities of using these regions for development of the transportation network is an important strategic task for the state. Today, in accordance with the Strategy for Spatial Development of the Russian Federation for the period up to 2025, the Arctic zone of the Russian Federation is a priority region in terms of economic growth and strategic impact.

The article analyses the impact of the technology of seasonally operating cooling devices on the foundation soils of Salekhard–Nadym section of the Northern Latitudinal Railway line (Kilometre points 2825+00 – PK 2830+00). The effectiveness of seasonally operating cooling devices on permafrost soils of the railway embankment foundation is shown in combination with heat-insulating material. The advantages and disadvantages of seasonally operating cooling devices are summarised.

Keywords: *transport, permafrost soils, roadbed, earthworks, cryolithic zone.*

For citation: *Shepitko, T. V., Artyushenko, I. A. Evaluation of Influence of Seasonally Operating Cooling Devices on Thermophysical Processes of Soils of Railway Embankment Base. World of Transport and Transportation, 2023, Vol. 21, Iss.1 (104), pp. 154–161. DOI: https://doi.org/10.30932/1992-3252-2023-21-1-2.*

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

Permafrost soils (PFS) are widespread in the territory of the Russian Federation, particularly in the Arctic zone of the country, which is one of the priority regions from the point of spatial development, economic growth, transportation, particularly through the Northern Sea Route. Thus, reliability of foundation structures is among the most significant elements enabling the effectiveness of civil engineering projects and long-term operation of infrastructure. To ensure it during designing, construction and operation of structures in the PFS zone it is necessary to adopt modern technology and monitoring tools.

The *objective* of the study, whose main results are described in the article, is the study of the impact of seasonally operating cooling equipment on the foundation soils on the example of the Salekhard–Nadym section of the Northern Latitudinal Railway line.

RESULTS

Modelling of Thermophysical Processes during Construction of Transport Facilities on Permafrost Soils

When designing structures on permafrost soils, to ensure their reliability, it is necessary to carry out thermophysical calculations and analyse the effect of the temperature regime on the earthworks [1–3].

To assess the thermal interaction of the railway embankment with the foundation soils, thermophysical calculations were made at Salekhard–Nadym section of the Northern Latitudinal Railway (NRL) (kilometre points 2825+00 – PK 2830+00). These calculations were performed with the Frost 3D software package, which has a certificate of conformity, a certificate of state registration of the software product and meets the requirements of the regulations RSN 67-68[1], SP 25.13330.2020[2], SP 116.13330.2012[3], SP 11-105-97 part IV[4].

The article analyses the influence of the temperature regime on the earthworks foundation and efficiency of seasonally operating cooling devices (SCD) at the above mentioned NLR section.

To calculate thermophysical properties and proceed with subsequent modelling of the temperature regime of soils, the data obtained from the results of engineering and geological surveys were used[5] (Table 1).

The area subject to calculations was selected as a cross section of the embankment on

[1] RSN [*Republic's construction standards*] 67-87. Engineering surveys for construction. Prediction of changes in the temperature regime of permafrost soils by numerical methods. RSFSR, Gosstroy publ., 1988, 73 p. [Electronic resource]: https://docs.cntd.ru/document/901708505. Last accessed 09.02.2023.

[2] SP [*Construction rules*] 25.13330.2020 Bases and foundations on permafrost soils SNiP 2.02.04-88: NIIOSP n.a. N. M. Gersevanov, 2021. [Electronic resource]: https://docs.cntd.ru/document/573659326. Last accessed 09.02.2023.

[3] SP [*Construction rules*] 116.13330.2012. Engineering protection of territories, buildings and structures from hazardous geological processes. Basic provisions. Updated edition SNiP 22-02-2003. Moscow, 2012, 65 p. [Electronic resource]: https://docs.cntd.ru/document/1200095540. Last accessed 09.02.2023.

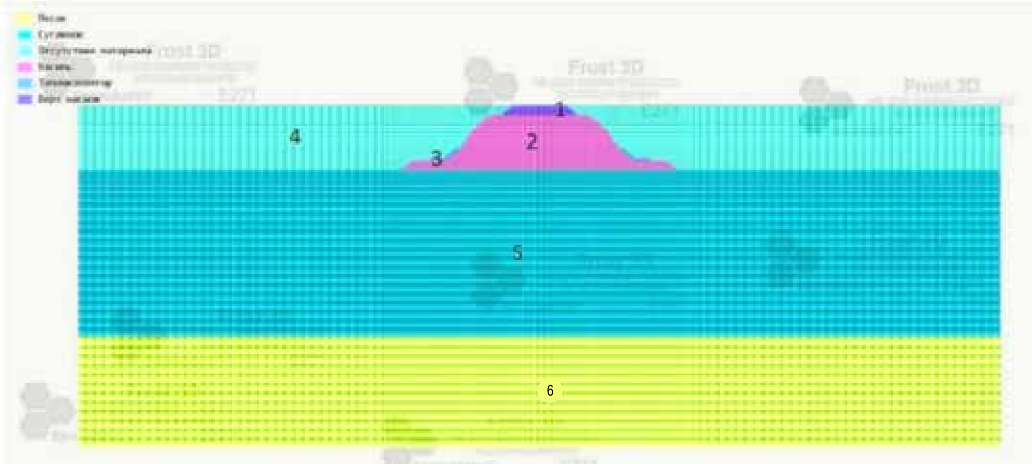
[4] SP [*Construction rules*] 11-105-97. Engineering and geological surveys for construction. Part IV. Rules for production of works in areas of distribution of permafrost soils. Moscow, 2000, 61 p. [Electronic resource]: https://docs.cntd.ru/document/1200007407. Last accessed 09.02.2023.

[5] Working project. Construction of a new Obskaya–Salekhard railway line. LLC Mostostroy-12, 2012, 278 p.

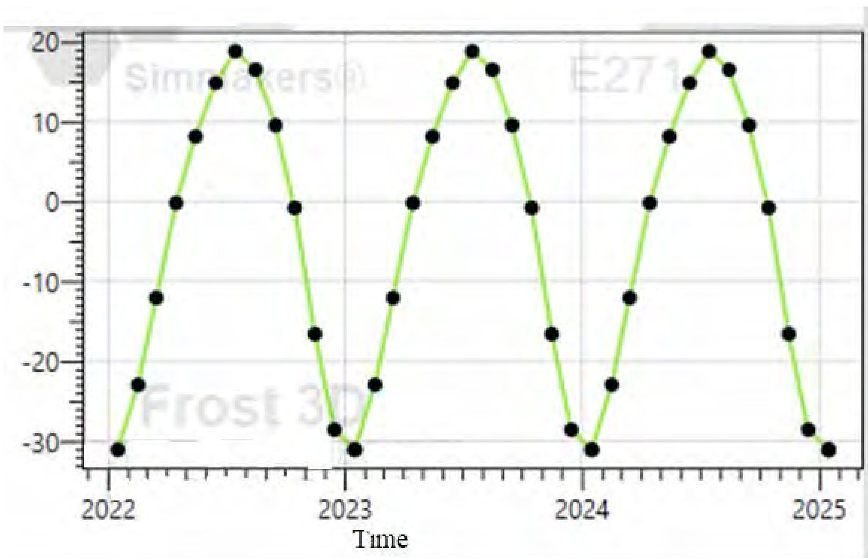
Table 1

Engineering and geological elements and thermophysical properties of soils used in modelling a geocryological forecast [performed by the authors]

Name	Humidity, unit fraction	Density of dry soil, kg/m³	Thermal conductivity, λ W/(m•K)		Specific heat capacity, °C kJ/(m³•K)		Freezing start temperature
			Frozen	Melted	Frozen	Melted	
Loam	0,25	1600	1,68	1,51	2,35	3,15	-0,20
Top of the embankment	0,05	1900	1,51	1,45	2,18	2,35	-0,05
Sand	0,38	1220	1,79	1,57	2,14	3,13	-0,28
Embankment	0,20	1400	1,86	1,57	1,89	2,48	-0,05



Pic. 1. Computational area at kilometre point PK 2825 presented in the Frost 3D software package: 1 – top of the embankment; 2 – embankment; 3 – heat insulator; 4 – lack of material; 5 – loam; 6 – sand [performed by the authors].



Pic. 2. Graph of temperature distribution per years [performed by the authors].

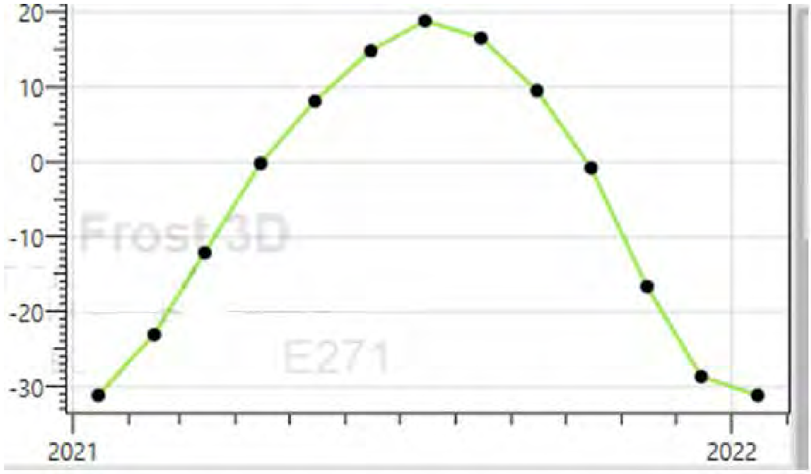
kilometre point 2825+00, which is a rectangular area of 15 m vertically and 50 m horizontally. This size of the calculation area captures all adjacent soils of the foundation and embankment for subsequent calculations. Pic. 1 shows the computational area with the contour breakdown of the soils used.

To model thermophysical properties, calculations were carried out to predict temperatures. While predicting temperatures, in each calculation area one can notice approximately the same temperature distribution graphs over the years (Pic. 2). The calculation is based on the temperature distribution graph for last available year data (Pic. 3).

Temperature data values for 2021 are presented in Table 2.

The calculated period of thermophysical properties was of 15 years (from January 15, 2022 to January 15, 2037), which showed changes in temperature fields.

Thermophysical models obtained during modelling with the Frost 3D software package are shown in Pics. 4 and 6. Comparing two models, it can be seen that initially there was a thawed zone in the body of the embankment, but with time its dimensions decrease to a minimum, and after freezing of the body of the embankment, the thawed zone is completely absent. Freezing occurs in the upper part of the

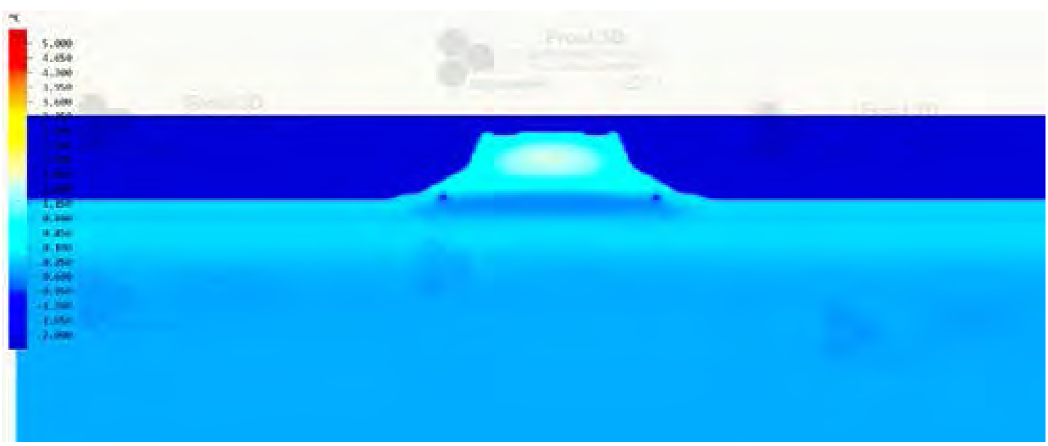


Pic. 3. Temperature distribution graph as for 2021 [performed by the authors].

Table 2

Temperature distribution table as for 2021 per months [performed by the authors]

Date	15.01.2021	15.02.2021	15.03.2021	15.04.2021	15.05.2021	15.06.2021	15.07.2021	15.08.2021	15.09.2021	15.10.2021	15.11.2021	15.12.2021	15.01.2022
Degrees	-31,1	-23	-12,1	-0,2	8,1	14,8	18,8	16,5	9,5	-0,8	-16,6	-28,6	-31,1



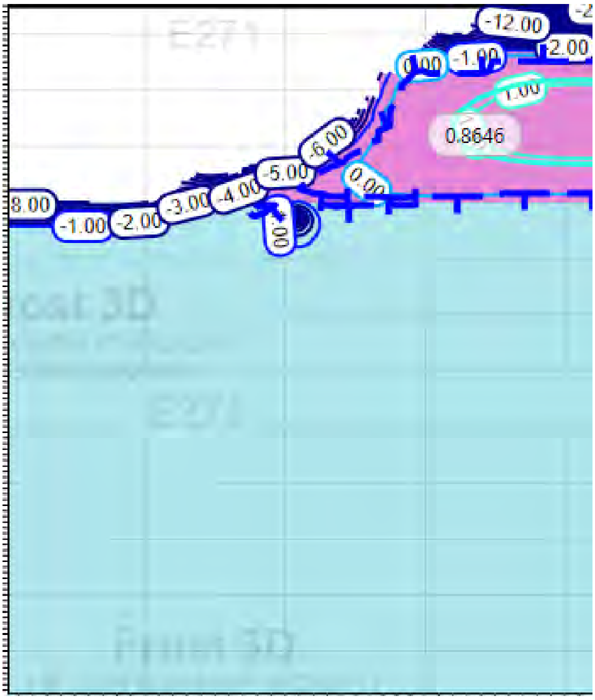
Pic. 4. Thermophysical model built in Frost 3D as for January 15, 2022 [performed by the authors].

embankment, which can be seen in the graphs of the distribution of temperature fields in Pics. 5 and 7.

Soils in the permafrost zone undergo seasonal thawing and freezing in the active layer. The active layer is the upper part of the permafrost, the change of which, following the change in heat transfer on the surface, leads to development of dangerous cryogenic processes [4; 5].

Based on the calculation results, the following conclusions can be drawn.

During the initial calculation for 2022, a thawed zone was identified in the centre of the embankment body. A thawed zone of this size can cause subsidence of the foundation soils and cause a violation of stability of the embankment. There is no thawed zone in the 2037 model, which is an important factor for ensuring stability of the embankment.



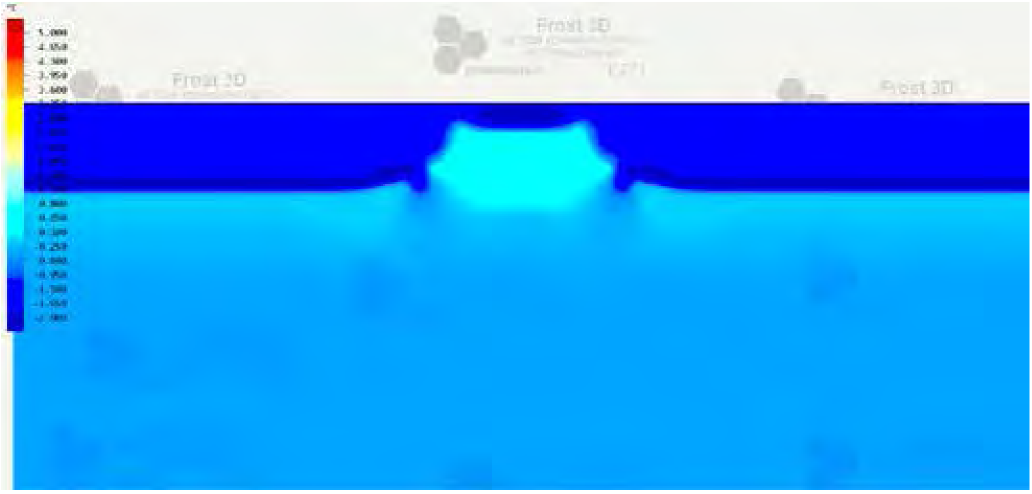
Pic. 5. Graph of distribution of temperature fields as for January 15, 2022 [performed by the authors].

Due to the results obtained, described in [6; 7], it is known that a post-cryogenic structure can appear within several years as a result of passage of cycles of freezing/thawing. The construction of the embankment leads to a change in the temperature regime of the foundation soils due to disturbance of the natural cover, which is clearly seen from the change in temperature fields over 15 years of the existence of the embankment. This leads to a decrease in ice-cementing bonds in frozen soils, as a result of which their strength characteristics decrease, which leads to an increase in deformations of the subgrade foundation [8].

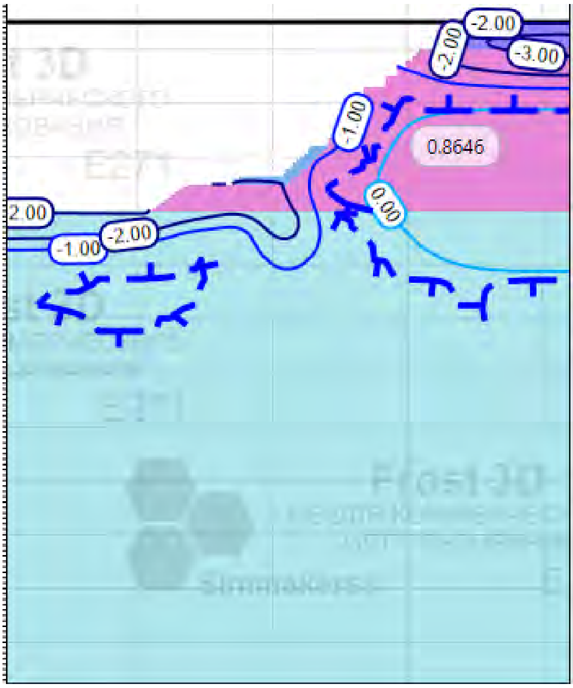
Modelling the Use of Seasonally Operating Cooling Devices (Using the Frost 3D Software Package)

The Frost 3D software package has extensive capabilities in calculating soil thermal stabilisation.

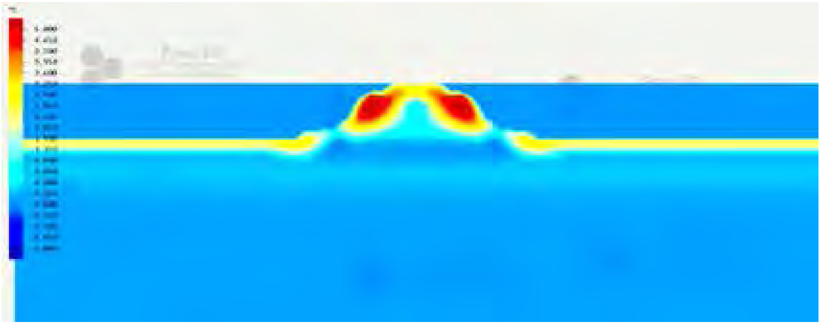
The studies [9–11] have disclosed the problem of thermal stabilisation of the temperature regime of the soils of the earthworks



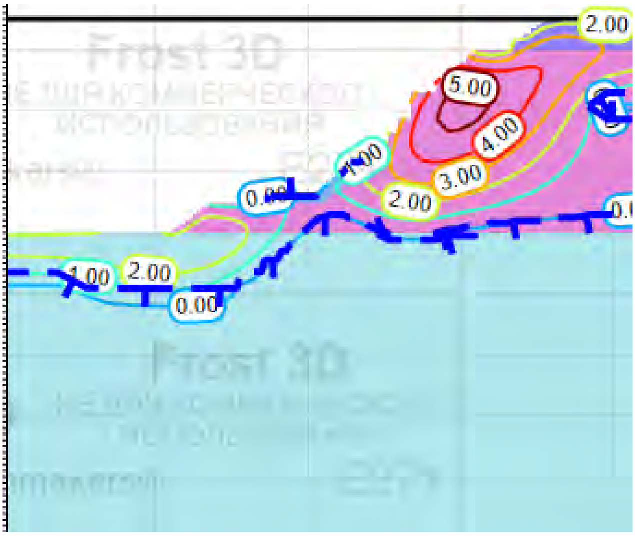
Pic. 6. Thermophysical model built in Frost 3D as for 15.01.2037 [performed by the authors].



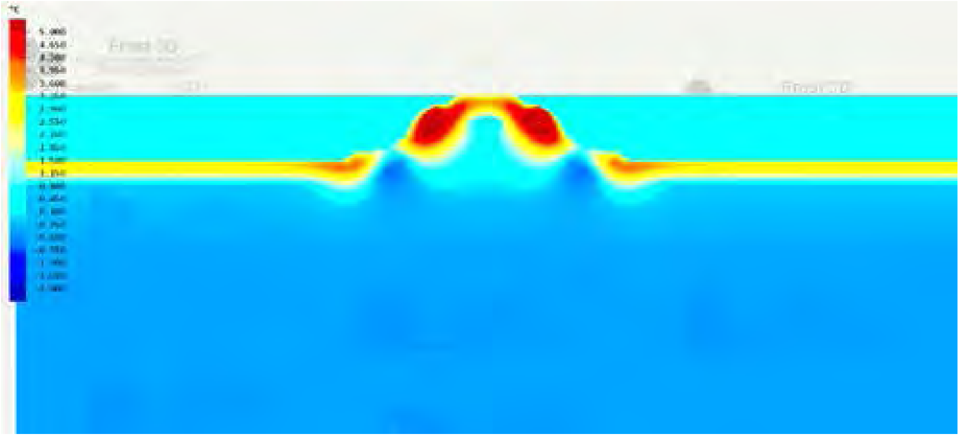
Pic. 7. Graph of distribution of temperature fields as for 15.01.2037 [performed by the authors].



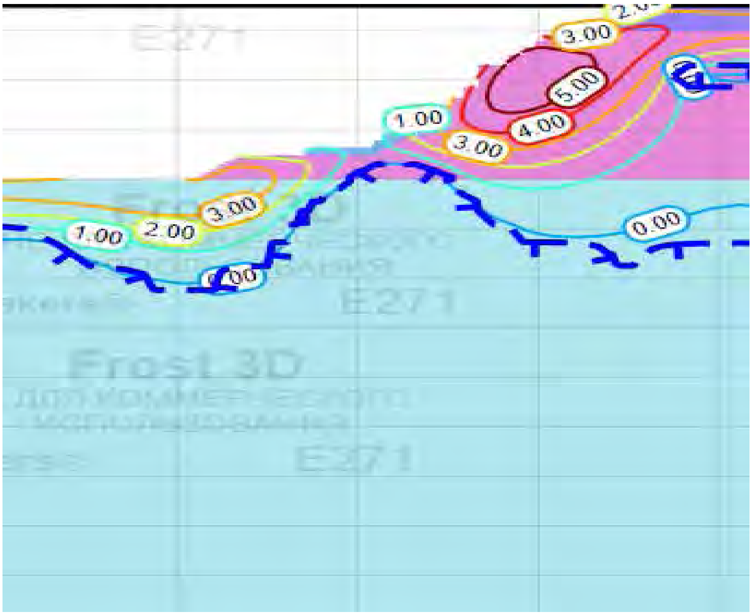
Pic. 8. Thermophysical model using SCD technology built in Frost 3D as for 15.10.2022 [performed by the authors].



Pic. 9. Graph of distribution of temperature fields using SCD technology as for 15.10.2022 [performed by the authors].



Pic. 10. Thermophysical model using SCD technology built in Frost 3D as for 15.10.2037 [performed by the authors].



Pic. 11. Graph of distribution of temperature fields using SCD technology as for 15.10.2037 [performed by the authors].

foundation to preserve the soils of the foundation in a frozen state and to prevent emergence of deformations in the foundation of the embankment.

The technologies for providing thermal stabilisation of permafrost soils comprise particularly the use of seasonally operating cooling devices (SCD) installed along the railway track.

The methodology for calculating the installation sites of seasonally operating cooling devices adopts mathematical solutions for cooling and freezing the soil around the cooling device [12–14].

When solving the problem of heat transfer between SCD and the soil, the system of differential equations (1) [15] is considered:

$$\begin{cases} c(T)\dfrac{\partial T}{\partial \tau} = \dfrac{1}{r} * \dfrac{\partial\left(r\lambda(T)\dfrac{\partial T}{\partial r}\right)}{\partial r} + \dfrac{\left(\partial(\lambda(T)\dfrac{\partial T}{\partial z}\right)}{\partial z}; \\ \lambda(T)\dfrac{\partial T}{\partial r} = K_s(v)\left(T - T_v(\tau)\right), \end{cases} \quad (1)$$

where r, z – are coordinates within the system of cylindrical coordinates;

τ – time;

$c(T)$ – effective volumetric heat capacity of rocks;

$\lambda(T)$ – coefficient of thermal conductivity;

$K_s(v)$ – evaporator thermal conductivity.

The use of the technology of SCD during construction and operation of the embankment has a positive effect on the temperature indicators of the foundation soils, and at the same time on physical and mechanical characteristics of these soils. To analyse the effectiveness of SCD, let's compare thermophysical models without the use of technology and with it (Pics. 6, 8).

In Pic. 6, as described above, there is a thawed zone in the centre of the embankment, which affects stability of the embankment. Compared to it, in Pic. 8, during the most dangerous month (October), the thawed zone progresses in the upper area, on the slopes and at the base of the embankment. SCD has a positive effect on the foundation soils, reducing the thawed zone at the slope boundaries. In Pic. 10, it can be seen that due to the influence of SCD and the heat-insulating material, the cooling zone grows, contributing to an increase in the strength characteristics of soils and stability of the embankment.

Comparing the models in Pics. 9 and 11, it can be seen that for 15 years there has been an active influence of positive temperatures, but due to the work of seasonally operating cooling devices and heat-insulating materials, the thawed zone has not spread so actively, preserving the zone of frozen soil.

CONCLUSIONS

Based on modelling of thermophysical processes within Salekhard–Nadym section of the Northern Latitudinal Railway line (kilometre points PK 2825+00 – PK 2830+00), the following conclusion can be drawn: the use of the technology of seasonally operating cooling devices has a positive effect on the foundation soils. However, the use of SCD is effective only when using the first principle of construction of soil structures: preservation of permafrost soils in a frozen state.

A significant disadvantage of operation of SCD is the need for their maintenance to ensure the efficient operation of those devices.

REFERENCES

1. Shepitko, T. V., Artyushenko, I. A., Dolgov, P. G. Base Soil Reinforcement with Vertical Crushed Stone Columns in Cryolithozone. *World of Transport and Transportation*, 2019, Vol. 17, Iss. 4, pp. 68–78. DOI: https://doi.org/10.30932/1992-3252-2019-17-68-78.

2. Shepitko T. V., Artyushenko I. A. The influence of vertical columns of crushed stone on the cryogenic processes of the soil base of the subgrade. *Russian Journal of Transport Engineering*, 2019, Vol. 6, Iss. 4, 11 p. DOI: http://dx.doi.org/10.15862/10SATS419.

3. Zheleznyak, I. I. Reliability of frozen foundations of structures [*Nadezhnost merzlykh osnovanii sooruzhenii*]. Novosibirsk, Nauka publ., 1990, 174 p. ISBN 5-02-029655-4.

4. Grechishchev, S. E., Chistotinov, L. V., Shur, Yu. L. Cryogenic physical-geological processes and their forecast [*Kriogennie fiziko-geologicheskie protsessy i ikh prognoz*]. Moscow, Nedra publ., 1980, 383 p.

5. Lutskii, S. Y., Roman, L. T. Technological control of permafrost soil characteristics in roadbeds. *Soil Mechanics and Foundation Engineering*, 2017, Iss. 3, pp. 26–30. [Electronic resource]: https://elibrary.ru/item.asp?id=30558316 [paid access].

6. Tsytovich, N. A. Bases and foundations on frozen soils [*Osnovaniya i fundamenty na merzlykh gruntakh*]. AS USSR publ., 1958, 168 p.

7. Kondratiev, V. G. New methods and technologies of managing the state of the body and foundation soils of a railway subgrade on permafrost. *Geotekhnika journal*. Moscow, LLC Geomarketing, 2011, Iss. 2, pp. 28–40. [Electronic resource]: https://elibrary.ru/item.asp?id=17649375 [restricted access].

8. Kudryavtsev, S. A., Sakharov, I. I., Paramonov, V. N. Freezing and thawing of soils (practical examples and finite element calculations) [*Promerzanie i ottaivanie gruntov (prakticheskie primery i konechno-elementnie raschety)*]. St. Petersburg, Georekonstruktsiya publ., 2014, 247 p. ISBN 978-5-9904956-3-0.

9. Ashpiz, E. S., Khrustalev, L. N. Prevention of degradation of permafrost soils at the base of railway embankments. *Earth's cryosphere*, 2020, Vol. 24, Iss. 5, pp. 45–50. DOI: 10.21782/KZ1560-7496-2020-5(45-50).

10. Jiankun, Liu; Yahu, Tian. Numerical studies for the thermal regime of a roadbed with insulation on permafrost. *Cold Regions Science and Technology*, 2002, Iss. 35, pp. 1–13. DOI: 10.1016/S0165-232X(02)00028-9.

11. Zolotar, I. A., Puzakov, N. A., Sidenko, V. M. Water-thermal regime of subgrade and pavement [*Vodno-teplovoi rezhim zemlyanogo polotna i dorozhnykh odezhd*]. Moscow, Transport publ., 1971, 414 p.

12. Ibragimov, E. V., Kronik, Ya. A., Kuplinova, E. V. Experimental Studies of Innovative Design of Soil Heat Stabilizers. *Vestnik of TSUAB*, 2014, Iss. 4, pp. 208–220. [Electronic resource]: https://www.elib.tomsk.ru/elib/data/2018/2018–1092/2018–1092.pdf. Last accessed 21.02.2023.

13. Ibragimov, E. V., Kronik, Ya. A., Pustovoit, G. P. Experience in the use of heat pumps as systems for thermal stabilisation of soil in permafrost [*Opyt ispolzovaniya teplovykh nasosov v kachestve sistem termostabilizatsii grunta v kriolitozone*]. *Soil Mechanics and Foundation Engineering,* 2015, Iss. 5, pp. 23–26. [Electronic resource]: https://www.nponorth.ru/nauchnaya-deyatelnost/publikacii/articleibragimov.pdf. Last accessed 21.02.2023.

14. Dolgikh, G. M., Okunev, V. N. Freezing and temperature stabilisation systems for soils in the permafrost zone, used by LLC NPO Fundamentstroyarkos. *Proceedings of IX scientific-technical conference «Simulation of artificial cold freezing technologies»*, 2003, pp. 123–129.

15. Kovalkov, V. P., Pronyaeva, T. I. Soil freezing intensification in oil and gas construction [*Intensifikatsiya zamorazhivaniya gruntov v neftegazovom stroitelstve*]. Moscow, Informneftegazstroy publ., 1981, 51 p. ●

Information about the authors:

Shepitko, Taisia V., *D.Sc. (Eng), Professor, Director of the Institute of Track, Civil Engineering and Structures of Russian University of Transport, Moscow, Russia, shepitko-tv@mail.ru.*

Artyushenko, Igor A., *Ph.D. (Eng), Associate Professor at the Department of Design and Construction of Railways of Russian University of Transport, Moscow, Russia, tywka351@mail.ru.*

Article received 22.02.2023, approved 03.03.2023, accepted 13.03.2023.