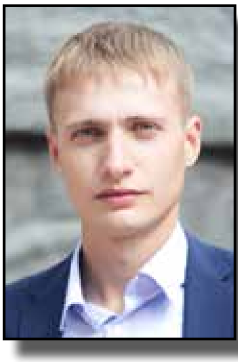
ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2024-22-1-1

World of Transport and Transportation, 2024, Vol. 22, Iss. 1 (110), pp. 152–162

Stabilisation of the Track's Subgrade Foundation by Injection in the Case of Degradation of Permafrost Soils

Denis A. RAZUVAEV



Roman S. PECHENKIN

***Denis A. Razuvaev* [1], *Roman S. Pechenkin* [2]**
[1, 2] Siberian Transport University, Novosibirsk, Russia.
[1] ORCID 0000-0003-0850-3414; Scopus Author ID: 57204687242; Russian Science Citation Index SPIN-code: 3250-0657; Russian Science Citation Index Author ID: 726831.
✉ *[1] razdenis@mail.ru.*

ABSTRACT

The location of the railway infrastructure on permafrost increases risks of emergence of defects and deformation of the subgrade. In Russia permafrost occupies approximately 65 % of the country's area. Consequently, defectiveness of subgrade in the Eastern part of railway network of Russia exceeds the network's average.

The objective of the study was the increase in the efficiency of stabilisation of track subgrade's foundation with injection method under the conditions of degradation of permafrost soils.

An improved algorithm for designing pressure injection of cement-soil grout, implementing an integrated approach, is proposed for railway subgrade operated under conditions of degradation of permafrost soils and formation of soft soils in foundations.

A laboratory experiment was set up and carried out to determine the amount of heat released by injected grout of various composition due to the exothermic reaction of hardening of cement, that allowed determining a linear dependence of the specific heat release of injection grout on the cement content.

A new calculation scheme with an equivalent layer of grout in the stabilisation area has been proposed to predict the amount of thawing of permafrost foundation soils when injecting materials with a cement binder, and an analytical solution to the problem under consideration has been proposed for preliminary calculations.

Keywords: *railway, subgrade, soils of subgrade's foundation, permafrost soils, degradation of permafrost soils, talik zone, soft soils, injection into soil, cement-soil grout, heat release of grout.*

Acknowledgements: *the work was carried out with the financial support of a grant from JSC Russian Railways under Agreement No. 5106471 dated December 28, 2022, provided for development of scientific and pedagogical schools in the field of railway transport.*

For citation: *Razuvaev, D. A., Pechenkin, R. S. Stabilisation of the Track's Subgrade Foundation by Injection in the Case of Degradation of Permafrost Soils. World of Transport and Transportation, 2024, Vol. 22, Iss. 1 (110), pp. 152–162. DOI: https://doi.org/10.30932/1992-3252-2024-22-1-1.*

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

INTRODUCTION

The Transport Strategy of the Russian Federation until 2030 with a forecast up to 2035 [1] provides for retrofitting of the infrastructure of Baikal-Amur and Trans-Siberian mainlines followed by increase in their transit and carrying capacity. In this regard, dependability and safety of the railway track, including the subgrade, are the main indicators that require special attention.

However, today the greatest risks that the Eastern segment of the Russian railway network is exposed to refer to the length of defective subgrade or subgrade being deformed. This is due to the location of a significant part of the railway infrastructure Eastern segment of the Russian railway network on foundations consisting of permafrost soils [1–3]. A change in the water-thermal regime of the subgrade–subgrade's foundation [2] system being operated under such complex natural, climatic, engineering and geological conditions causes degradation of permafrost soils (permafrost) with formation of talik zones with low bearing capacity in the subgrade's foundations [3–5].

Similar problems are observed in several other countries, such as China [6; 7] and Canada [3], with similar natural and climatic conditions and presence of permafrost in the natural foundation bed of engineering structures.

This requires development and implementation of new effective solutions for stabilisation of track subgrade's foundations. One of the possible effective ways to increase the physical and mechanical characteristics of soft soils in talik zones is the method of pressure injection of soil-cement grout, which has proven itself in stabilising weak foundations [8; 10; 11].

At the same time, it is worth noting the disadvantages of the pressure injection method, if it is used to stabilise thawed soils in subgrade's foundation. First, it refers to disruption of heat exchange [10; 11] in the subgrade's foundation during the period of injection and hardening of the cement-soil grout due to its own heat and to exothermic processes within the cement binder [4]. These processes lead to further thawing of permafrost soils, and formation of a layer of soft tabetisol directly under the consolidated massif. Second, consolidation of the subgrade's foundation using the pressure injection method has virtually no effect on the water-thermal regime of the subgrade – subgrade's foundation system and the conditions for heat exchange between the structure and the atmosphere during the period of further operation. Under the conditions in which the position of the permafrost boundary has not stabilised, further degradation of permafrost soils is possible, also leading to formation of soft soils under the stabilised massif and to ground subsidence.

To eliminate the negative consequences of thawing of permafrost soils during the injection process, an algorithm for designing iterative injection was proposed in [10]. According to the proposed algorithm, injection is designed using standard technology, but in several steps (iterations). With each subsequent iteration, a significantly smaller amount of grout is used, and the thawing effect is significantly reduced. The design of stabilisation is completed at the injection iteration with which the thawing effect does not cause ground subsidence at the subgrade's foundation in excess of permissible values. However, the design algorithm proposed by the authors in [10] is applicable only under conditions of stabilisation of the position of the permafrost soil boundary within the subgrade's foundation, which sharply limits the scope of its application.

Therefore, the *objective* of the study is to increase the efficiency of stabilisation of the railway track's subgrade's foundation with the injection method during degradation of permafrost soils. The paper offers proposals for improving the method of designing pressure injection of cement-soil grout for subgrade's foundations with permafrost soil, exposes the results of a laboratory experiment to determine the amount of heat released by injection grout, and also proposes to discuss the calculation scheme and method for predicting the rate of thawing of permafrost subgrade's foundation when using injection.

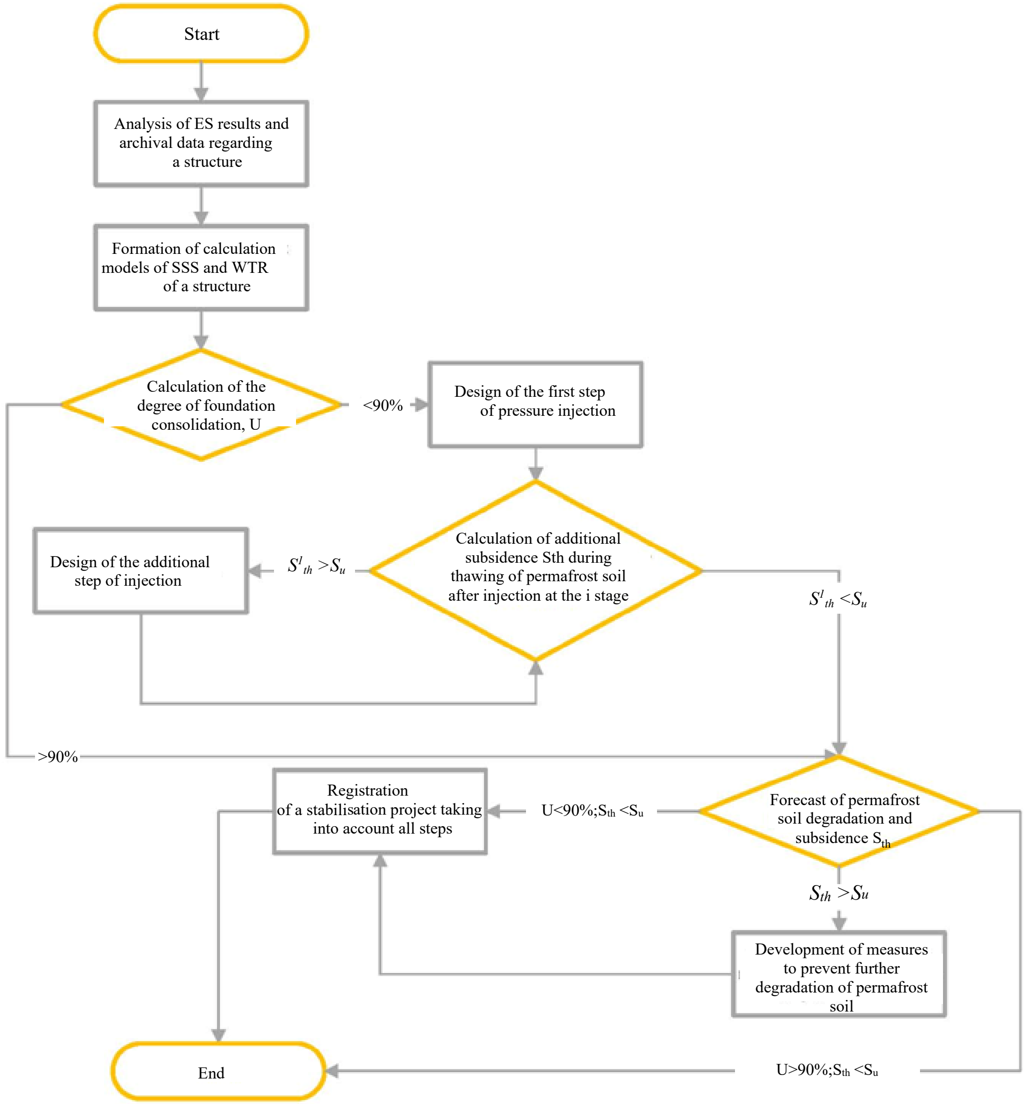
---

[1] The Transport Strategy of the Russian Federation until 2030 with a forecast up to 2035 as approved by the Order of the Government of the Russian Federation dated 27.11.2021 № 3363-r [Electronic resource]: http://static.government.ru/media/files/7enYF2uL5kFZlOOpQhLl0nUT91RjCbeR.pdf.

[2] Subgrade's foundation in the context of the paper and considering differences in terminology used in research works means natural ground or subsoil underlaying track foundation, embankment, formation, including subgrade. – *Ed. note for English translation.*

[3] UCalgary researcher heads up major federal permafrost study in Manitoba [Electronic resource]: https://schulich.ucalgary.ca/news/ucalgary-researcher-heads-major-federal-permafrost-study-manitoba. Last accessed 08.02.2024.

[4] Guidelines for concreting foundations and lines of communication in permafrost soils, taking into account concrete hardening at low temperature. Stroyizdat publ., NIIZhB of Gosstroy of the USSR, 1982., 160 p.



Pic. 1. Improved algorithm for designing pressure injection of cement-soil grout for foundations with permafrost soil [developed by the authors]: ES – engineering surveys; SSS – stress-strain state; WTR – water-thermal regime; S_u – permissible subsidence of the subgrade's foundation; S_{th} – foundation subsidence due to changes in the total WTR at the construction site.

RESULTS

Improving the Method of Designing Pressure Injection

To adapt the method to real, widespread operating conditions of the railway track (the position of the permafrost soil boundary has not been stabilised), it is proposed to approach the design of pressure injection of cement-soil grout into permafrost subgrade's foundations in a comprehensive manner. That is, to provide and carry out calculation rationale for a set of measures aimed at increasing the bearing capacity of soils in talik zones, as well as at stabilising the position of the boundary of permafrost within subgrade's foundation.

An improved algorithm for designing pressure injection of cement-soil grout for subgrade's foundations with permafrost soil, implementing an integrated approach, is shown in Pic. 1.

According to the proposed algorithm, the decision to increase the physical and mechanical characteristics (stabilisation) of soils in talik zones is made based on the condition of completing the filtration consolidation of the foundation, and the decision to stabilise the position of the permafrost soil boundary in the foundation is made based on the condition of not exceeding the limit values of track subsidence arising from degradation.

Based on these conditions, the calculation can result in obtaining one of the following four solutions:

– Stabilisation on the site is not required.

– Stabilisation of soft soils in talik zones is required without stabilising the position of the permafrost soil.

– Stabilisation of the position of the permafrost soil boundary is required without improving the characteristics of soils in talik zones.

– A comprehensive solution is required to stabilise soils in talik zones and the position of the permafrost soil boundary.

To stabilise soft soils, it is recommended to proceed with several steps of pressure injection of cement-soil grout [10], whilst to stabilise the position of the permafrost soil boundary, it is recommended to select one of the effective measures for thermal stabilisation [6; 12–16]. After all the assigned measures have been implemented, mechanised track straightening is envisaged.

The pressure injection provided by the algorithm is carried out through vertical and inclined injectors from the subgrade's slopes, and in the case of two or more tracks, additionally from the inter-track space beyond track clearance [8; 9; 17]. This arrangement of injectors allows work to be performed with imposing minimal restraints on train movement, and in some cases, without constraints [17]. All work must be carried out between passage of trains in accordance with the current rules for technical operation of the track.

During the process of injection and further operation of the subgrade with some thermal stabilisation, the temperature field of the subgrade – subgrade's foundation system is monitored. Monitoring is carried out using thermometric wells made before the work is carried out. Wells are installed in accordance with current regulatory requirements for measuring transverse profiles from the roadsides, at the bottom of the subgrade, between tracks (if necessary), and in the right-of-way (control wells). The distance between the measuring transverse profiles is assigned during design and depends on the length of the injected section of the subgrade's foundation and its engineering and geological features. Control of the bearing capacity of the subgrade's foundation is carried out using static or dynamic probing methods using mobile installations [9; 17].

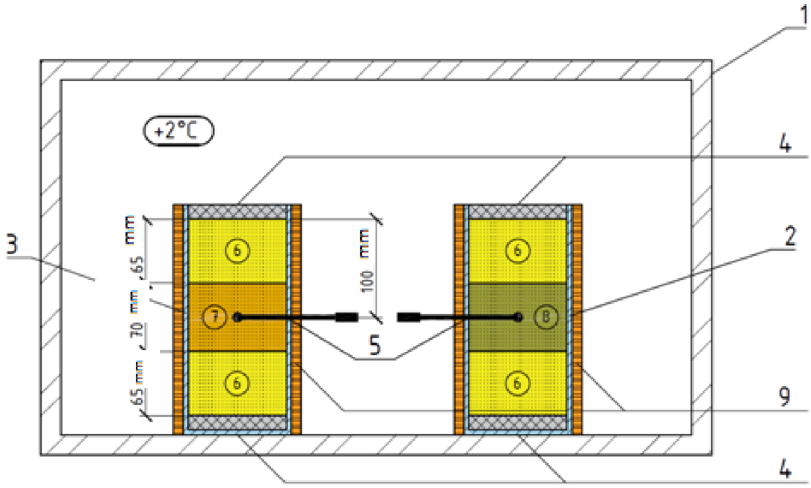
The comprehensive solution proposed in the design algorithm (Pic. 1) allows not only to solve the problem of soft soils in talik zones, but also to stabilise the position of the permafrost soil boundary. The positive technical effect of using this solution, in contrast to classical methods of thermal stabilisation, is a significant acceleration of the stabilisation process with obtaining results in a fairly short time; the economic effect is a significant reduction in the number and/or power, and, accordingly, in the cost of thermal stabilisation devices.

Setting Up, Conducting of a Laboratory Experiment and its Results

To further develop the computational and theoretical apparatus of the above-mentioned improved method for designing the stabilisation of subgrade's foundations with permafrost soils, a laboratory experiment was set up and carried out to determine the volume of heat released by injected grout of various composition due to the heat of hardening of cement.

The use of the known dependences[4] of the heat release of Portland cement or grouts or mortars (concrete) based on it [18] for the problem being solved is not possible for a number of reasons. First, injection cement-soil grouts have a significant difference [17] from general construction mortars and concrete, both in terms of the water-cement ratio and in terms of composition, since varying ratios of clay and sandy soils are usually used as the main structural filler. Second, the existing dependencies, as a rule, were obtained for normal temperature and humidity conditions corresponding to the conditions of hardening of concrete and mortars in building structures. The hardening conditions of injection grout, especially when used in subgrade's foundation thawed soils with close occurrence of permafrost soil, differ significantly from normal ones, and obviously affect heat generation due to the exothermic reaction of hardening of cement.

The analysis of existing methods and approaches to determining the heat release of cement during hardening showed that such studies mainly use calorimeters with adiabatic or isothermal hardening modes. The adiabatic mode when determining the heat release of concrete during hardening is provided for by both domestic (GOST [State Standard] 24316) and international (EN 12390–15:2019, NEQ) regulatory documents. Isothermal calorimeters



Pic. 2. Calorimeter for determining the amount of heat release of injection grouts using «soil – grout – soil» models [developed by the authors]: 1 – body of the thermostatic chamber; 2 – mold for the tested model sample; 3 – mold for the alternative model sample; 4 – cooling plates with thermoelectric modules and temperature sensors; 5 – temperature sensors; 6 – soil part of the model sample; 7 – soil grout in the alternative model sample; 8 – cement-soil grout in the tested model sample; 9 – external thermal insulation of molds with model samples.

are usually used to determine heat release during hardening of cements[5] (GOST 310.5; BS EN 196–11:2018), or to study model concrete mortars [18].

The adiabatic mode implies the absence of heat exchange between the system under the study and the surrounding environment with a natural increase in the temperature of the tested sample. Isothermal mode involves testing in a thermostated chamber, in which the heat generated by the sample dissipates quickly enough and its temperature remains constant. In this case, the heat release is determined by the difference between the heat release of the samples under the study and the samples selected for comparison [hereinafter called alternative models]. The main disadvantage of the adiabatic mode is considered to be a continuous and significant increase in the temperature of the samples (higher than under real conditions of construction sites), which leads to self-acceleration of the heat release process [18]. Isothermal calorimeters maintain a given hardening temperature that corresponds to real conditions, however, there are restraints on the size of the tested samples, so studies are carried out on finely dispersed solutions or models of concrete mix ratios [18; 19].

As noted earlier, the hardening conditions of injection grout when used in subgrade's foundation thawed soils with close occurrence of permafrost soil differ significantly from the conditions in building structures, therefore the use of the above-described modes for studying heat release processes is not possible. Under the conditions under consideration, cement-soil injection grout will harden in the soil mass at fairly low temperatures. Besides, the temperature of the injection grout during hardening under such conditions will decrease. This is due to its heat exchange within the subgrade's foundation with a large volume of cooled (0…+4 °C), water-saturated clay soils with a fairly high heat capacity. Such conditions are not simulated in either an adiabatic or an isothermal calorimeter.

Therefore, a calorimeter was designed based on the hardware and software of the GT 1.1.12 NPP Geotek device to perform the experiment on «soil – grout – soil» models under conditions close to those described above.

The experiment (Pic. 2) consisted of cooling with a fixed heat flow of constant power of thermostated «soil – grout – soil» models (samples) and an alternative model. The alternative model used grout (7, Pic. 2) without adding cement. The calorimeter elements and the soil part (6) in the models were thermostatically brought to a setpoint temperature of +2 °C (indicative temperature

[5] E.g.: An experimental comparison between isothermal calorimetry, semi-adiabatic calorimetry and solution calorimetry for the study of cement hydration (NT TR 522) [Electronic resource]: https://www.nordtest.info/wp/2003/03/28/an-experimental-comparison-between-isothermal-calorimetry-semi-adiabatic-calorimetry-and-solution-calorimetry-for-the-study-of-cement-hydration-nt-tr-522. Last accessed 08.02.2024.

Table 1

Compositions of the tested injection grouts

№ of the composition sample	Material consumption for preparing 1 litre of grout, g		
	Cement (CEM I 42,5N)	Soil*: Sandy loam with I_p=5	Water
1	300	1650	180
2	350	1600	220
3	400	1550	260
4	450	1500	270
5	500	1450	360

* soil used in injection practices, providing a ratio of clay and sand particles close to optimal [17].

of thawed soils of subgrade's foundation); while grouts (7, 8, Pic. 2) were thermostatically brought to a setpoint temperature of +24 °C (temperature for preparing injection grouts at the site during the warm season). Based on the ratio of the cooling time of the tested models and the alternative model to the setpoint temperature of +2 °C, the specific heat release of injection grouts of various composition was subsequently calculated due to the exothermic reaction during cement hydration process. To cool the models, thermostated cooling (+2 °C) plates (4, Pic. 2) with thermoelectric modules and temperature sensors were installed at their ends.

The time of the experiment was limited by the time of cooling of the model samples to +2 °C according to data from temperature sensors (5, Pic. 2), but not less than 3 days. Temperature from sensors was recorded at intervals of no more than 5 minutes. With further hardening of the grout under real conditions (more than 3–7 days), heat generation continues, but in a much smaller amount, which can be neglected in engineering calculations.

The tested and alternative models were reduced to an equal model heat capacity C_{mod}. This was achieved by changing the mass of the soil grout (m_s+m_{ws}) in the alternative model samples until the following condition was met:

$$c_s m_{sc} + c_w m_{wc} + c_c m_c = c_s m_s + c_w m_{ws}, \quad (1)$$

where c_s – specific heat capacity of dry soil in grout, J/(kg·K);

c_w – specific heat capacity of water in grout, assumed to be 4190 J/(kg·K);

c_c – specific heat capacity of cement in cement-soil grout, assumed to be 800 J/(kg·K);

m_{sc} – mass of soil in the cement-soil grout of the tested model, kg;

m_{wc} – mass of water in the cement-soil grout of the tested model, kg;

m_c – mass of cement in the cement-soil grout of the tested model, kg;

m_s – mass of soil in the soil grout of the alternative model, kg;

m_{ws} – mass of water in the soil grout of the alternative model, kg.

When changing the mass of the soil grout in the alternative model according to (1), the proportion $\frac{m_s}{m_{ws}} = \frac{m_{sc}}{m_{wc}}$ was obligatorily maintained.

The experiment's initial stage involved preparation of a cement-soil grout (8, Pic. 2) for the tested model samples and a soil grout (7, Pic. 2) for the alternative model samples. All materials for the grouts had been preliminarily thermostated to setpoint temperature of +24 °C, and the soil had been dried. The compositions of the tested cement-soil grouts are given in Table 1; the compositions of soil grouts for alternative models were selected according to the method described above.

Immediately after preparing the grout, the tested and alternative model samples were prepared in molds (2, Pic. 2) and (3, Pic. 2) preliminarily thermostated to setpoint temperature of +2 °C (Pic. 3). Sandy loam of plastic consistency, water-saturated and thermostated to setpoint temperature of +2 °C, was used as the soil component of the model sample (6, Pic. 2).

In the process of conducting (Pic. 4) a laboratory experiment (cooling of thermostated «soil – grout – soil» model samples), graphs of temperature changes were plotted in the middle of the experimental models. The experiment was completed with stable thermostatic control of the system and model samples at +2 °C, maintaining this state for at least a day (the total time of the experiment was at least 3 days). The cooling times of the tested model samples t_1 and alternative models t_2, respectively, were recorded based on the resulting graphs.

It is known that the heat flow power is determined by the formula

$$N = Q/t, \quad (2)$$

a) b) c)

Pic. 3. Experimental model samples making [developed by the authors]: a) the molds to be used in the calorimeter; b) alternative model sample with soil grout; c) tested model sample with cement-soil grout.

where Q is the amount of heat transferred to the system, J; t – time, sec.

Considering that the plates with thermoelectric modules (4, Pic. 2) cooled the tested model samples (with cement) and the alternative model sample (without cement) with the same power, but for different times, t_1 and t_2, respectively, and assuming that due to the presence thermal insulation, the plates cooled only the model samples without consuming power for remaining elements of the system, the expression can be deemed correct:

$$\frac{Q_{mod}}{t_2} = \frac{Q_{mod} + Q_c}{t_1}, \quad (3)$$

where Q_{mod} is the amount of heat transferred from the plates (4, Pic. 2), for cooling (thermostating to +2°C) model samples of equal heat capacity, J;

Q_c is the amount of heat transferred from the plates (4, Pic. 2), to compensate for the heat release of cement during hardening in the tested model, J.

Then, $Q_c = Q_{mod} \cdot \left(\frac{t_1}{t_2} - 1\right)$. (4)

Considering that the final temperature value of the previously thermostated soil component of the model sample did not change, and the entire amount of heat Q_{mod} compensated for cooling of the soil grout in the model samples, then, taking into account equation (1):

$$Q_c = (c_s \cdot m_s + c_w \cdot m_{ws}) \cdot \Delta T \cdot \left(\frac{t_1}{t_2} - 1\right), \quad (5)$$

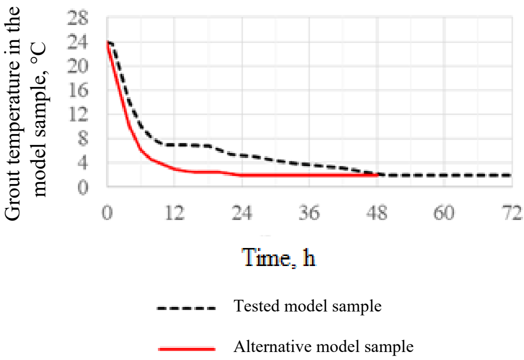
where ΔT is the change in the temperature of the soil grout in the model, *K*.

The specific heat release of injection grouts due to the hydration of cement during hardening, in kJ per litre of material, is calculated as:

$$q_c = 0,001 \cdot \frac{Q_c}{V_{is}}, \quad (6)$$

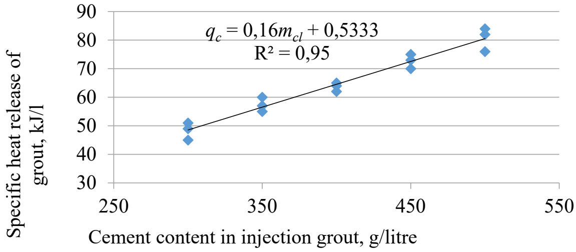
where V_{is} is the volume of the grout in the model samples, assumed to be 0,5495 l.

For each of the studied compositions (Table 1), a series of three laboratory experiments was performed, the results of which revealed the



a) b)

Pic. 4. Conducting a laboratory experiment [developed by the authors]: a) general view of the installation; b) an example of a temperature graph in the middle of the tested model sample for composition No. 3 and for alternative model sample, respectively, over time.



Pic. 5. Dependence of the specific heat release of injection grouts on the cement content when injecting soft soils in talik zones [developed by the authors].

dependence of the specific heat release of injection grouts q_c on the cement content m_{cl} (in the interval from 300 to 500 g/l), shown in Pic. 5.

RESULTS AND DISCUSSION

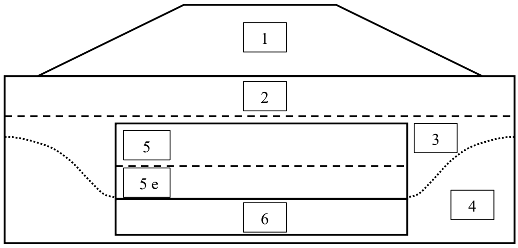
The identified dependence (Pic. 5) can be approximated by a linear function:

$$q_c = 0,16m_{cl} + 0,5333, \quad (7)$$

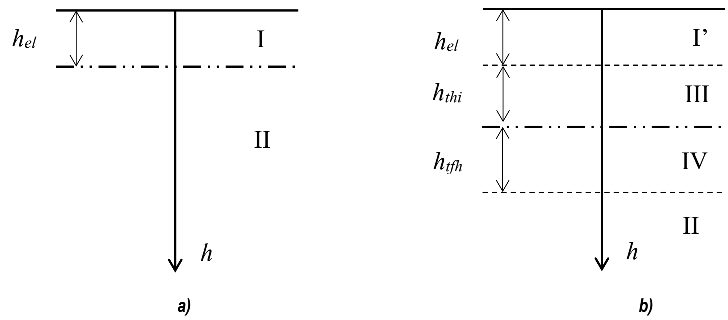
which is further proposed to be used to predict the rates of heat released by injection grouts of various composition due to the exothermic reaction of hardening of cement when designing pressure injection of cement-soil grouts into the talik zones of subgrade's foundations containing permafrost soils. This dependence considers both the hardening conditions of injection grouts under the conditions under consideration and the features of their composition. For other injection conditions that differ significantly from those considered in the work, it is recommended to directly determine the specific heat release of the injection grout using the method described above.

Also, a calculation scheme with an equivalent layer is proposed for discussion (Pic. 6) to predict the permafrost soils thawing rate value h_{thi} in subgrade's foundations when injecting cement grouts. The outline of the railway embankment (1, Pic. 6) on the design diagram, as well as the boundaries between consolidated (2, Pic. 6), unconsolidated (3, Pic. 6), and permafrost (4, Pic. 6) soils of subgrade's foundation, and as a result, the shape of the talik zone is taken based on the results of engineering surveys at a specific site.

The zone of injection stabilisation of subgrade's foundations (5, Pic. 6) is assigned based on the results of the stress-stain state assessment, considering the actual structure and composition of the soils composing it. Based on the results of calculations of the bearing capacity and subsidence of the subgrade's foundation, the width and thickness h_{sl} of the zone to be stabilised are assigned. To ensure the required physical and mechanical characteristics of the stabilised subgrade's foundation, the weighted average coefficient of reinforcement of the zone of stabilisation with grout k_a is selected, considering the number of engineering geological elements in this zone and their relative volume. In practices [17], the grout in the zone of stabilisation spreads chaotically, in the form of arrays, pillars and interlayers, bands, which complicates thermal engineering calculations. Therefore, to determine the rate of permafrost soil thawing within subgrade's foundation h_{thi} during injection, it is proposed to use a calculation scheme (Pic. 6) with an equivalent layer of solution 5 *e* of the



Pic. 6. Calculation scheme for predicting the rate of thawing of permafrost soil within the subgrade's foundation when injecting cement-soil grouts [developed by the authors]:
1 – railway embankment; 2 – consolidated clayey soils within subgrade's foundation; 3 – unconsolidated clayey soils within subgrade's foundation; 4 – permafrost soils within subgrade's foundation; 5 – zone of stabilisation of soils of subgrade's foundation by injection of cement-soil grouts; 5 e – equivalent layer of grout in the stabilisation zone; 6 – zone of thawing (degradation) of permafrost soil due to heat release of the injection grout.



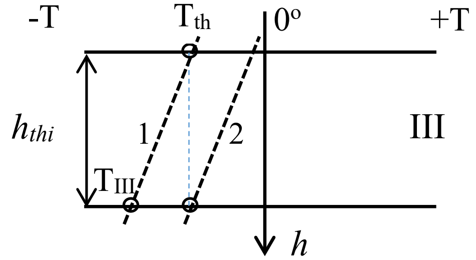
Pic. 7. Feature zones during thermal interaction of cement-soil grouts and permafrost soil during injection [developed by the authors]: a) before injection; b) after injection.

thickness h_{el} in the lower part of the stabilisation zone (at the top of the permafrost soil).

This approach does not either introduce significant errors into thermal engineering calculations, but also corresponds to the real conditions of pressure injection, when the grout spreads into the zones of the least consolidated soils of subgrade's foundation. Wherein:

$$h_{el} = k_a \cdot h_{sl'} \quad (8)$$

The thickness of the zone h_{thi} of thawing of permafrost soils of subgrade's foundation (6, Pic. 6) is recommended to be determined using specialised software packages with assignment of an internal heat source in the form of an equivalent layer in accordance with the proposed calculation scheme. The amount of total heat release should be determined depending on the initial temperature and composition of the injection grouts, as well as the specific heat release q_c, determined from test results or dependence (7) when injecting similar materials and under conditions similar to those considered in the work. Based on the results of calculating the thickness of the thawing zone, in accordance with the pressure injection design algorithm (Pic. 1), it is possible to evaluate the additional subsidence of the foundation S_{thi} during the thawing of the permafrost soil, as well as to assess the need and number of additional steps (iterations) of injection.



Pic. 8. Scheme of temperature changes in zone III after injection and stabilisation of the temperature background [developed by the authors]: 1, 2 – temperature field before and after thawing of permafrost soil, respectively.

Also, a simplified method for predicting the value of h_{thi} is proposed for engineering calculations. Such simplified calculations are used in the Guidelines[4], however, for the problem being solved, their use is not justified, since they use design schemes, materials and some thermophysical parameters that do not correspond to the conditions under consideration.

It is proposed to solve this problem in a one-dimensional formulation along the axis of the embankment, and to consider at the first stage the thermal interaction of zone I, with thickness h_{el} with soft soils within subgrade's foundation in a thawed state and the average temperature T_I, and zone II, represented by permafrost soils of subgrade's foundation (Pic. 7 *a*). Thermal parameters of soils in these zones are determined based on survey results. Since, in general, the work considers the conditions of degradation of permafrost soil, the temperature at the boundary of thawed and frozen soils is taken to be T_{th} – the temperature at which the soil ends thawing.

After injection (Pic. 7 *b*), soft soils of zone I are considered as an equivalent layer of grout (5 *e*, Pic. 6) with a thickness h_{el}. This zone (I') is the zone for calculation of heat released by the injection grout with an initial temperature T_{sc} and thickness h_{el} due to its own heat and the heat of hardening of cement. The amount of heat released in this zone will be:

$$Q_{I'} = \begin{bmatrix} \left(c_s \cdot m'_{sc} + c_w \cdot m'_{wc} + c_c \cdot m'_c\right) \cdot \\ \cdot \left(T_{sc} - T_{I'}\right) + q_c \cdot 10^6 \end{bmatrix} \cdot h_{el} \cdot a, \quad (9)$$

where m'_{sc}, m'_{wc}, m'_c are respectively, the consumption of soil, water and cement in the design cement-soil grout (for preparing 1 m³), kg/m³;

$T_{I'}$ – temperature of zone I' after complete hardening of the grout and stabilisation of the temperature in the surrounding soil (we assume $T_{I'} \approx T_I$, K);

a – coefficient, equal to 1 m².

In zone III with thickness h_{thi}, degradation of permafrost soil occurs due to heat release of the injection grout. The amount of heat absorbed by this zone consists of the heat necessary for the ice–water phase transition, as well as the heat necessary to increase the temperature of first frozen and then (after the phase transition) thawed soils:

Опять формула не просматривается – можно взять из русского, она там правильная?

$$Q_{III} = \begin{bmatrix} \lambda_i \cdot \rho_d^{tf} \cdot (W_{tot} - W_w) + \\ + \left(\frac{c_{tf} + c_{th}}{2}\right) \cdot (T_{th} - T_{III}) \end{bmatrix} \cdot h_{thi} \cdot a \,, \quad (10)$$

where λ_i is specific heat of melting of ice, J/kg;

ρ_d^{tf} – skeletal density of permafrost soils, kg/m³;

W_{tot} – total humidity content of permafrost soils, unit fractions;

W_w – humidity of permafrost soils due to unfrozen water, unit fractions;

c_{tf} – specific heat capacity of permafrost soils, J/(m³·K);

c_{th} – specific heat capacity of thawed soil, J/(m³·K);

T_{III} – maximum negative temperature of permafrost in zone III before injection according to survey data, K.

Expression (10) is valid when the temperature in zone III changes according to the scheme shown in Pic. 8.

In zone IV, with thickness h_{tfh}, the permafrost soil temperature increases due to the heat release of the injection grout. The amount of heat absorbed by this zone will be:

$$Q_{IV} = c_{tf} \cdot \left(\frac{T_{th} - T_{III}}{2}\right) \cdot h_{tfh} \cdot a \,. \quad (11)$$

Since the structure and composition of soils in zones III and IV are heterogeneous, physical features of soils. including their heat capacity, used in (10) and (11), are recommended to be calculated based on their average values within the considered zones.

Assuming that the main part of the heat release from the injection grout will be ultimately aimed at thawing permafrost soils within subgrade's foundation, without significant heat dissipation through a significant thickness of overlying soils into the atmosphere, the expression is correct:

$$Q_{I'} = Q_{III} + Q_{IV}, \quad (12)$$

and then h_{thi} can be found through analytical solution (13) at the bottom of the page that allows us to solve the problem of predicting the amount of thawing of permafrost soils during injection based on data obtained from the results of engineering surveys at the site, as well as on solutions and proposals obtained in this work.

CONCLUSION

To increase the efficiency of stabilisation of the railway subgrade's foundation during degradation of permafrost soil, the method for designing pressure injection of cement-soil grouts has been improved and adapted to real, widespread operating conditions of a railway track on a soft subgrade's foundation during thawing of the permafrost soil.

The setup and conduction of a laboratory experiment as well as its results have been described allowing to determine the amount (Pic. 5) of heat released by injection grouts of various compositions due to the exothermic reaction of hardening of cement.

A calculation scheme is proposed for predicting the amount of permafrost soil thawing within the subgrade's foundation when injecting cement-soil grouts for thermal engineering calculations in specialised software packages. In addition, an analytical solution for engineering calculations has been proposed (13). In the future, it is possible to improve the obtained analytical solution based on identification of some empirical coefficients.

The results obtained make it possible to predict the h_{thi} amount of thawing of permafrost soils in subgrade's foundations when injecting cement grouts and to subsequently evaluate the additional subsidence S_{thi} of the subgrade's foundation, as well as the need and number of additional iterations of injection.

$$h_{thi} = \frac{\left[\left(c_s \cdot m'_{sc} + c_w \cdot m'_{wc} + c_c \cdot m'_c\right) \cdot \left(T_{sc} - T_{I'}\right) + q_c \cdot 10^6\right] \cdot h_{el} - c_{tf} \cdot \left(\frac{T_{th} - T_{III}}{2}\right) \cdot h_{tfh}}{\lambda_i \cdot \rho_d^{tf} \cdot (W_{tot} - W_w) + \left(\frac{c_{tf} + c_{th}}{2}\right) \cdot (T_{th} - T_{III})}. \quad (13)$$

REFERENCES

1. Sazonov, V. N., Ashpiz, E. S. Current problems of ensuring reliability of the subgrade at the Eastern part of railway network [*Aktualnie problem obespecheniya nadezhnosti zemlyanogo polotna na Vostochnom poligone*]. *Zheleznodorozhniy transport*, 2015, Iss. 9, pp. 28–31. EDN: UJYKOH.

2. Lanis, A. L., Razuvaev, D. A. Engineering survey of the foundation of the subgrade on the approaches to bridges in the permafrost soil zone (using the example of Lopcha – Khogochi section of the Far Eastern Railway). *Polytransport systems: proceedings of IX International Scientific and Technical Conference*, Novosibirsk, November 17–18, 2016. Siberian State Transport University. Novosibirsk, SGUPS, 2017, pp. 113–117. EDN: ZWVQLJ.

3. Kudryavtsev, S. A., Kazharsky, A. V., Valtseva, T. Yu. [*et al.*] Structures for strengthening railway embankments on permafrost soils during construction of the second tracks of the Eastern part of railway network [*Konstruktsii usileniya zheleznykh dorog na vechnomerzlykh gruntakh pri stroitelstve vtorykh putei Vostochnogo Poligona*]. *Proektirovanie razvitiya regionalnoi seti zheleznykh dorog*, 2016, Iss. 4, pp. 243–250. EDN: XEEXQJ.

4. Lanis, A. L., Razuvaev, D. A. Systematization of features and requirements for geological survey of railroad subgrades functioning in cold regions. *Sciences in Cold and Arid Regions,* 2017, Vol. 9, Iss. 3, pp. 205–212. DOI: 10.3724/SP.J.1226.2017.00205. EDN: XOEQKD.

5. Ashpiz, E. S., Vavrinuk, T. S. Computation of Deformations of Embankments in Permafrost Areas. *World of Transport and Transportation*, 2012, Vol. 10, Iss. 3(41), pp. 102–107. EDN: PCDSHT.

6. Harris, S. A. The Tibetan Railroad: Innovative Construction on Warm Permafrost in a Low-Latitude, High-Altitude Region. In: Engineering Earth: The impacts of megaengineering projects. Springer Science and Business Media, 2011, Chapter 43, pp. 747–765. DOI: 10.1007/978-90-481-9920-4_43.

7. Liu, H.; Huang, S.; Xie, C.; Tian, B.; Chen, M.; Chang, Z. Monitoring Roadbed Stability in Permafrost Area of Qinghai–Tibet Railway by MT-InSAR Technology. *Land*, 2023, Vol. 12, Iss. 2, 474. DOI: https://doi.org/10.3390/land12020474.

8. Ashpiz, E. S., Vavrinyuk, T. S. Strengthening deformed long-term exploited embankments on permafrost [*Usilenie deformiruyushchikhsya dlitelno ekspluatiruemykh nasypei namnogoletnemerzlom osnovanii*]. Polytransport systems: proceedings of IX International Scientific and Technical Conference, Novosibirsk, November 17–18, 2016. Siberian State Transport University. Novosibirsk, SGUPS, 2017, pp. 86–90. EDN: ZWVQJL.

9. Lanis, A. L. Application of the pressure injection method to strengthen embankments [*Primenenie napornoi inektsii dlya usileniya nasypei*]. *Put i putevoe khozyaistvo*, 2009, Iss. 6, pp. 33–35. EDN: PXHCMF.

10. Lomov, P. O., Lanis, A. L., Razuvaev, D. A., Kavardakov, M. G. Stabilizing subgrades of transport structures by injecting solidifying grouts in cold regions. *Sciences in Cold and Arid Regions*, 2021, Vol. 13, Iss. 5, pp. 357–365. DOI: 10.3724/SP.J.1226.2021.21040. EDN: DKSADH.

11. Sakharov, I., Kudryavtsev, S., Paramonov V. [*et al.*] Ensuring the operational suitability of buildings, railways and bridges in of the Arctic zone in conditions of global warming // X International Scientific Siberian Transport Forum – TransSiberia 2022, Novosibirsk, March 02–05, 2022. Novosibirsk, Elsevier B.V., 2022, pp. 2506–2514. DOI: 10.1016/j.trpro.2022.06.288. EDN: GXCWVQ.

12. Ashpiz, E. S. Experience in construction of railway subgrade located on permafrost soils: problems and ways to solve them [*Opyt sooruzheniya zemlyanogo polotna zheleznykh dorog, raspolozhennykh na mnogoletnemerzlykh gruntakh: problemy i puti ikh resheniya*]. *Bulletin of the Joint Academic Council of JSC Russian Railways*, 2019, Iss. 1, p 1–27. EDN: TQJHVX.

13. Kondratyev, V. G., Valiev, N. A. Technology and results of additional cooling of the slopes of the subgrade on the central section of the BAM [*Tekhnologiya i rezultaty dopolnitelnogo okhlazhdeniya otkosov zemlyanogo polotna na tsentralnom uchastke BAM*]. *Kulagin readings: equipment and technologies of production processes: XV International scientific and practical conference: Collection of articles in 3 parts, Chita, November 30 – December 02, 2015. Part 3*. Chita, Transbaikal State University, 2015, pp. 156–161. EDN: VHKJST.

14. Passek, V. V., Kraev, A. N., Paskov, M. V., Andreev, V. S. Stabilization of the temperature regime of soils of the foundations of structures in complex frozen-soil conditions of the polar and subpolar tundra [*Stabilizatsiya temperaturnogo rezhima gruntov osnovanii sooruzhenii v slozhnykh merzlotno-gruntovykh usloviyakh zapolyarnoi i pripolyarnoi tundry*]. *Bulletin of the Tyumen State University of Architecture and Civil Engineering*, 2015, Iss. 4, pp. 89–93. EDN: VHLWLR.

15. Passek, V. V., Vorobiev, S. S., Poz, G. M., Passek, V. V. Surface cooling system for an embankment in a permafrost zone [*Sistema poverkhnostnogo okhlazhdeniya nasypi v zone vechnoi merzloty*]. *Put i putevoe khozyaistvo*, 2024, Iss. 1, pp. 2–6. EDN: NLTQVZ.

16. Kudryavtsev, S. A., Valtseva, T. Yu., Kotenko, Zh. I., Gavrilov, I. I. Forecasting processes of freezing and degradation of permafrost foundations of embankments [*Prognozirovanie protsessov promerzaniya i degradatsii mnogoletnemerzlykh osnovanii nasypei*]. *Put i putevoe khozyaistvo*, 2022, Iss. 4, pp. 34–35. EDN: DQWLLR.

17. Lanis, A. L. Reinforcement of operated high embankments with injection of hardening grouts. D.Sc. (Eng) thesis [*Armirovanie ekspluatiruemykh vysokikh nasypei s inektirovaniem tverdeyushchikh rastvorov. Diss.. dokt. tekh. nauk*]. Moscow, RUT publ., 2019, 409 p. EDN: YYKKOJ.

18. Barannik, N. V., Kotov, S. V., Potapova, E. S., Malakhin, S. S. Determination of the concrete heat emission during its hardening in isothermal conditions. *Bulletin of Science and Research Center of Construction*, 2022, Iss. 2 (33), pp. 44–62. DOI: 10.37538/2224-9494-2022-2(33)-44-62.

19. Wadsö, L. Operational issues in isothermal calorimetry. *Cement and Concrete Research*, 2010, Vol. 40. Iss. 7, pp. 1129–1137. DOI: https://doi.org/10.1016/j.cemconres.2010.03.017. ●

Information about the authors:

Razuvaev, Denis A., *Ph.D. (Eng), Associate Professor, Head of the Research Laboratory of Quality Control of Road Pavements and Roadbeds of Siberian Transport University, Novosibirsk, Russia, razdenis@mail.ru.*

Pechenkin, Roman S., *Ph.D. student, Engineer of Siberian Transport University, Novosibirsk, Russia, roma.pechenkin@yandex.ru.*

Article received 07.02.2024, approved 14.03.2024, accepted 27.03.2024.