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Technological Features of Construction and Reconstruction of Geotechnical Structures in the Arctic Zone

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Abstract: Production engineering methods and geotechnical instrumentation for the construction and reconstruction of railway beds in high temperatures in the Arctic zone are proposed. High-technology construction facilitates the development of transport infrastructure of the energy-producing industries in the Arctic. The example of the Northern Latitudinal Railway (NLR) highlights the probability of dangerous cryogenic processes and phenomena during works, such as waterlogging and the structural decline of the active soil layer, the development of taliks, and frost cracking, which lead to a decrease in bearing capacity of soil. The features of the construction and production plans used at the sites of railway embankment reconstruction with heavy-duty equipment are outlined. New process control methods have been developed based on the selection of and systematic changes in the parameters of maximum permissible construction loads depending on the results of geotechnical structure monitoring. The structural diagram of high technology for strengthening the weak subgrade soil under the conditions of talik development is substantiated. In order to regulate intensive process parameters, the vehicle fleet needs to be equipped with positioning devices and automation process control systems. The effectiveness of process control in terms of improving the reliability and accelerating roadbed consolidation is substantiated.

Keywords: geotechnical structure; technology; construction; reconstruction; permafrost zone

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1. Introduction

The construction and reconstruction of railroads in the permafrost zone is relevant to the Strategy for Developing the Russian Arctic Zone and Ensuring National Security until 2035 [1], as well as the key areas of the Social and Economic Development of the Arctic Zone of the Russian Federation state program. Transport infrastructure expansion is aimed at improving accessibility and logistics in the development of new fields of energy resources. The findings of permafrost studies conducted in the Arctic point to the manifestation of dangerous cryogenic processes and phenomena, including waterlogging and the structural decline of the active soil layer, talik development, and the frost cracking of the soil, that lead to a decrease in its bearing capacity. All this will inevitably escalate during the construction of new natural and man-made systems. Special considerations should be also observed with respect to transport infrastructure given the increased risk of the limiting states of subgrade soil and drainage structures at all phases of the life cycle (survey, engineering, construction, and operation) in accordance with the federal law 384-FZ [2]. It should be noted that the existing rules and regulations [3–5] and fundamental works on the construction of geotechnical facilities in permafrost [6–8] are mainly focused on the safety of commissioned objects, and do not sufficiently take into account how their characteristics change during the construction period. At the same time, during the course of construction and installation works, the risk of permafrost degradation in the right of way, as well as deformations of exposed and incomplete foundation and structure sections, increases significantly.

The design experience following the construction of sections in the Northern Latitudinal Railway [9] and the Obskaya–Bovanenkovo–Karskaya railway line revealed the development details of the process regulations, which are as follows.

1. The production plan for roadbed construction can be diverse and includes work on both new and operating facilities (Figure 1). Geotechnical engineering and new construction technology are designed to carry out work in conditions of frozen soil with low-temperature permafrost (the first principle) and with the assumption of the thawing of high-temperature permafrost soils (the second principle). Both principles include structural and technological solutions for safety and protection against the degradation of new natural and transport systems at all life cycle phases. New construction is scheduled on the Obskaya–Salekhard section, and changes will take place on the Nadym–Pangody section. When reconstructing the roadbed of operating Pangody–Novy Urengoy–Korotchaevo railway lines, it is necessary to take into account the temperature patterns in the base of these structures.

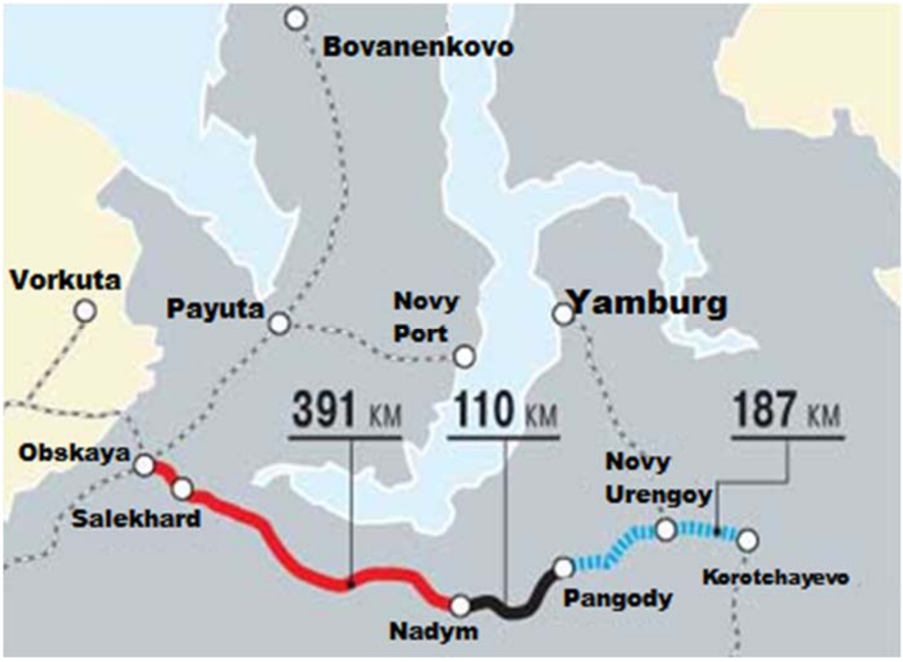


Figure 1. The construction plan for geotechnical structures in the Arctic zone.

Technological features of the reconstruction have been established during the development of specifications for the engineering and construction of the Nadym–Pangody Railway Line [9,10] project. They are related to the safety requirements for three different types of work: (a) the extension to the existing track with ledges—32.66% of the total length of the sections; (b) embankments over the existing track—43.58%; and (c) new structures—23.76%. According to the engineering surveys, water-saturated fine silty sands and loams with high plasticity classified as heaving soil with low load-bearing capacity are widespread along the route.

2. The use of intensive process parameters at the subgrade base depends on the presence of dangerous cryogenic processes and phenomena that are activated during the construction period and lead to a decrease in the bearing capacity of the subgrade support. With this, excavation in frozen or thawing soils is possible only with the use of heavy equipment with high loads. Moreover, in accordance with [11], soil compaction should be carried out with a load close to the limit of their strength. These

strict safety requirements for incomplete and unprotected structures are boundary conditions for the development of process parameters.

3. The risks of a dangerous combination of the load limits of an unfinished structure increase during the stage of construction with the use of heavy-duty equipment. They are associated with the conditions of a multi-kilometer work front, different types of artificial structures (bridges and pipes), and the heterogeneity of the soil composition along the longitudinal and transverse profiles of embankments and excavations. Under these conditions, it is necessary to calculate the risk of subgrade stability violation from the construction machinery, at which point the safe load for soils (taking into account the pore pressure) Fb [12] does not conform to the technological impact. The limit is determined by the probability that the Fb value will be less than the process load Fm and the constructed part of the facility Fs:

$$Pt = p[Fb - (Fm + Fs)/Kn] < 0, \tag{1}$$

This condition needs to be checked in the course of work on a systematic basis, with the continuous diagnosis and prevention of limiting states in real time, especially when it comes to slopes and sidehills [13,14].

2. Materials and Methods

The high technology [6,7] developed by experts at the Russian University of Transport and patented with the use of process and automated control systems (Figure 2) meets the requirements for the safety of the geotechnical facilities under construction. The proposed schematic diagram of subgrade soil-strengthening technology includes preliminary and main construction periods. Its purpose and novelty are reflected in the possibility of adjusting construction load and impact parameters based on geotechnical subgrade monitoring [15–17] in real time. The Process Control Center, the main unit, receives and synthesizes data obtained from geodetic and parametric monitoring and geophysical studies, calculates the bearing capacity of soils, and compares it with the load parameters of machinery (vibratory compactors, pile driving equipment, impact machinery, etc.) to determine the modes of operation.

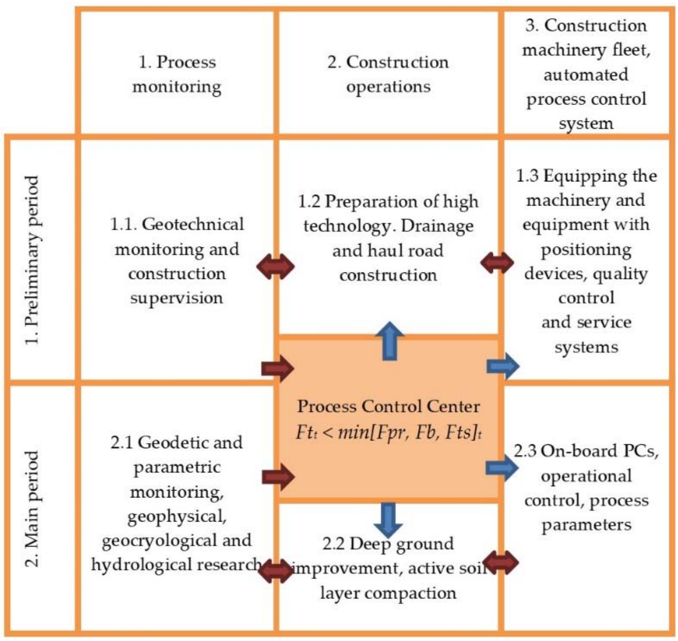


Figure 2. The technological structure of strengthening the subgrade support in the construction period (Ft_t—process load; Fpr—ultimate strength of the soil, Fb—safe load for the weak layer; Fts—thixotropic load limit in period t).

Unit 1.1 enables the geotechnical monitoring (GM) [17,18] of the given specific features of the linear facilities in the preliminary period of subgrade construction to diagnose the condition and predict the stability of the weak base under the loads immediately before and during the works in real time. The preliminary period anticipates the establishment of a Process Control Center, including fixed and mobile stations and monitoring observation networks for consolidated calculations to (a) assess and forecast the facility state according to data from the GM units, construction operations, and the machinery fleet; (b) calculate the limit loads and impacts of condition (1); and (c) develop safe process parameters for the works. Unit 1.1 of geotechnical monitoring includes a subsystem that can control the base stresses using fiber optic sensor cables. Developing the synthesis of all GM types' results with modeling and calculations of the base state [9,15] in conjunction with Units 1.2 and 2.2 is the Process Control Center's key objective.

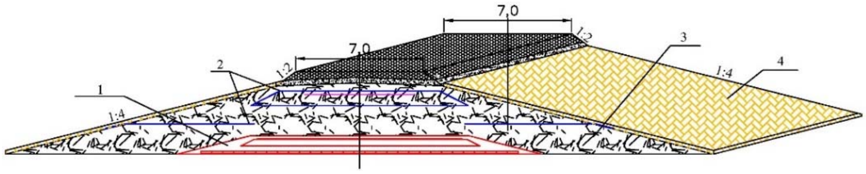
Unit 1.2 includes earthwork planning with the use of high technology, upgraded together with Giprotransproekt JSC in the development of project specifications. Work projection in the preconstruction compaction mode to increase the bearing capacity and reduce base deformations in the area adjacent to existing embankment slopes is envisaged in areas of roadbed reconstruction located on water-saturated loam soils (where design is carried out according to principle (II)), water-saturated fine sands, and iced soils. In areas of high and excessive heaving soils, soil replacement is provided for the frost heave depth of the layer [19,20]. Preconstruction compaction technology comprises:

- Tapping transverse water pockets to create drainage ditches and forming a protective layer based on the roadbed transverse profile's projected type (further construction at the embankment top, side extension, or a new structure);
- Sealing the subgrade through a protective layer in autumn with a vibratory compactor to expel water inflow during the period of migration moisture accumulation.

As for the preproduction stage (Unit 1.2), the specifications [8] include proposals for the construction of a highway as a haul road for the transportation of soil and construction vehicles. In areas providing neither access for vehicles nor the possibility to drive on the existing Novy Urengoy–Nadym regional road, it has been proposed to build a haul road on the reconstructed embankment of the existing line (Figure 3), given the operation service restrictions on the transportation of construction cargo and shift teams.

(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Building of a haul road: (**a**) executing works; (**b**) fitting the haul road into the embankment transverse profile (1—haul road, 2—geotextile holder, 3—embankment, 4—peat sand mix).

Unit 1.3. The preliminary period also enables the preparation of a fleet of mobile road construction vehicles and equipment, as well as maintenance services for work in a permafrost zone. The fleet shall be equipped with vehicles and machinery adapted to the arctic climate, permitting automatic load adjustments depending on the hazardous processes on site.

Unit 2.1. In the main construction period, all geotechnical monitoring subsystems (geodetic and parametric monitoring and geophysical and hydrological studies) should operate in conjunction with the operational control of Unit 2.3. Readings of all subsystems need to be interconnected at a certain moment of work using modern equipment and software for calculations and the modeling of geocryological and geophysical studies [21]. The GM functions fundamentally differ from the roadbed monitoring during operation in their focus on the process control of production activity.

Monitoring control operations, with particular regard to the temperature curves and characteristics of thawed and frozen soils in the subgrade, should be linked to construction deadlines. According to this collated information, the Process Control Center (Figure 2) is able to check the safety of the technological load *Ft* of construction machines, which should not exceed: (1) the ultimate strength of the soil *Fpr*; (2) the safe load for the weak layer *Fb*; (3) the thixotropic limit *Fts* in period t. A statistical profile exploring the relationships between deformation and the strength characteristics of melting and thawed soils is highly relevant for summary calculations and conclusions on operation safety [22,23]. In particular, the analysis of thawed and frozen soils carried out on the engineering survey data to construct the Obskaya–Salekhard subgrade has made it possible for the determination of deformation property dynamics. The statistical profile [10] showed (Figure 4) that the average flow index value IL of frozen soils (1.51) almost doubles after thawing compared to thawed cohesive soils (0.78). The suggested conclusion indicates the need to use high technology for water expulsion and the reduction of the moisture content of soils in the subgrade before the erection of the embankment.

Unit 2.2 includes the development of engineering and process solutions for the high-level compaction of the active layer and deep soil improvement on thawed zones using geosway and geodrains. The high technology involves vibratory compactors or impact machinery working in limited conditions while enabling the process control of loads up to a maximum permissible size.

As the load conditions of the compactor become more intensive, unfrozen water content in the freezing upper soil layer increases in autumn. As a result, this causes a decrease in the bearing capacity. The compactor parameters are to be specified further to soil tests and the safety factor calculation for each base layer. When calculating the dynamic load from the vibratory compactor, the safe limit should be considered:

$$Ft_t\ (Pk, At, Vt, vt) < min[Fpr, Fb, Fts]_t, \tag{2}$$

where Ft_t is the load depending on the contact rigidity of the soil layer and vibrating roll parameters (*Pk* weight, *A* amplitude, *V* speed, and *v* frequency); *Fpr* is the ultimate strength of the soil; *Fb* is the safe load for the weak layer considering dynamics and reliability coefficients; *Fts* is the thixotropic load limit in period *t* of high technology (working shift).

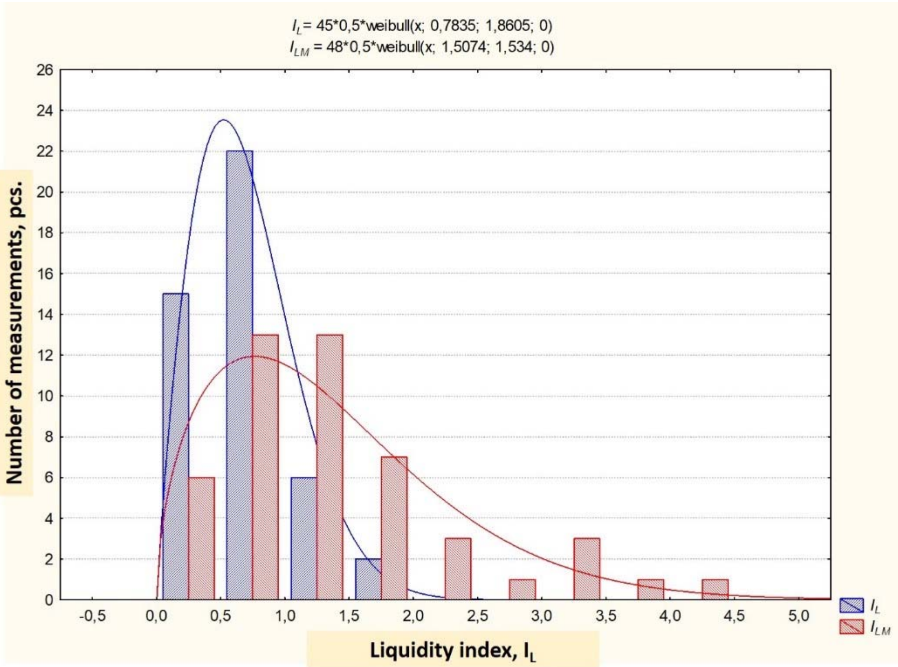


Figure 4. Distribution of the flow index of thawed *IL* and frozen IL_m (during thawing) cohesive soils in the Obskaya–Salekhard line section.

Unit 2.1 should ensure the simultaneous compliance control of current soil conditions and the regulated parameters of the compactor (amplitude, frequency, speed, and type of vibration). The process control of loads by condition (2) enables a flexible real-time response to the limit of soil in each layer. This conclusion is proven by the statistical profile of cohesive thawed soil conditions in the roadbed base obtained from the results of engineering surveys in the Obskaya–Salekhard line [24].

The soil structure is loose after thawing, the values of the deformation modulus decrease and, accordingly, the potential deformations of the base increase at low density. The consistent application of the drainage system device processes, vibration compaction, and water expulsion simultaneously reduce humidity, increase soil density, and reduce the deformability of the structure. Moreover, the mode of water expulsion in the subgrade allows for accelerating the period of both consolidation and road construction [24].

3. Discussion and Results

High technology for deep subgrade improvement with the cutting and replacement of weak heaving soil, as well as the installation of piles and geodrains, should be carried out in conjunction with geophysical studies. The deep improvement of the roadbed subgrade on thawed and swampy areas with peat cutting and replacing it with sand mass and immersing showed the danger of residual layers of uncompacted soil between the mass and the mineral bottom of the swamp [24]. These areas require comprehensive monitoring that includes electrical resistivity exploration, seismic refraction with data processing via seismic tomography, georadar surveying using mobile units, and groundwater studies with the installation of observation wells. Geophysical studies are meant to monitor the state of the mass and pore pressure, as well as model additional technological processes to improve the weak layer by limit loads, taking into account condition (2).

Unit 2.3 is intended to regulate the construction mechanizing parameters in dangerous areas by using construction machinery with automated control, integrated with high technology. For instance, to ensure the process control of earthworks and installation, it is effective to use equipment with an automated process control system made by Caterpillar and Komatsu, including autonomous earthmoving machines (excavators, bulldozers, etc.) as well as quarry dump trucks with on-board control and navigation equipment for hazardous works in automatic or remote mode. BOMAG and Dynapac soil compactors are equipped with an automated quality control system that enables the user to adjust speed, amplitude, frequency, and oscillation mode.

Junttan and Liebherr equip drilling machines with a control system to continuously monitor the position, depth, pile profile, and consumption and pressure of concrete in each pile. The automated process control system makes it possible to determine the structure of base layers and calculate the bearing capacity of piles and to stop work and change the loads and the position of each machine in cases of emergency.

Thus, regulating the process parameters on thawed weak bases while monitoring limits in real time ensures safety and the reduction of the geotechnical structures' consolidation period at the construction stage.

Developing a process control system responsible for the safety of construction loads and impact based on real-time subgrade geotechnical monitoring is the key result of this research.

4. Implementation

The proposed high technology and geotechnical monitoring system were implemented in 2009–2019 as part of the process regulations for constructing the sections of the Obskaya–Bovanenkovo–Karskaya and Berkakit–Tommot–Yakutsk railway lines developed by the Autonomous Educational Institution of Higher Education "Russian University of Transport" (MIIT) in the course of preparing the project specifications for the Nadym–Pangody NLR section. The application of high technology at the construction site of the Nadym–Salekhard road made it possible to reduce moisture and increase the safety factor of the active soil layer from 0.96 to 1.31. The research was carried out as part of the Strategic Partnership Agreement between the Yamal-Nenets Autonomous Area Government and the Russian University of Transport signed in 2013 and updated in 2018.

5. Conclusions

1. Subgrade construction in the permafrost zone can be expediently performed with the application of the developed high technology and geotechnical monitoring of mechanical and thermo-physical processes while regulating the permissible limits of construction loads. The process control system proposed in line with the monitoring enables the reduction of the moisture content and deformability of soil and can shorten the base consolidation period.
2. The construction of railroads features challenging engineering and geological, as well as permafrost, conditions for work and the activation of hazardous natural processes at unfinished structures. The risks of soil deformation and structural decline in the right of way increase due to the impact of heavy construction equipment and the diversity of the production program for constructing various structures on the multi-kilometer frontline works. Meanwhile, current regulatory documents lack reliability assessments of organizational and process solutions during the construction and reconstruction of the subgrade in high-temperature permafrost.
3. To implement the high technology for improving weak soil in the permafrost, it is expedient to provide a control plot with geotechnical monitoring and develop a process control system for construction that includes interrelated units of preparation for production and the automated control of the machinery in real time.

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