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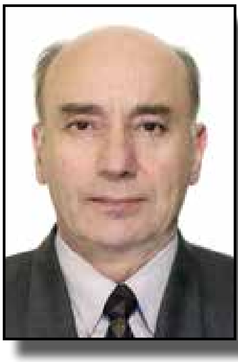
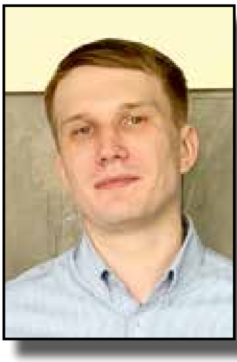
# Technical Regulation and Monitoring of Subgrade Construction in the Arctic





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## ABSTRACT

*The study outlines the technology for increasing the bearing capacity of the subgrade foundation on high-temperature permafrost soils in the Arctic zone with the objective to develop technological regimes for strengthening the weak foundation of embankments, allowing for regulation of loads during construction of facilities on permafrost soils. The research methods included system analysis and the methods specific for organising construction in the permafrost zone. The described methodology consists of step-by-step modelling and calculation of parameters for geotechnical monitoring of the condition of the subgrade to determine the maximum permissible technological loads.*

*The tasks and functions of the system for regulating and monitoring technological operations are determined to specifically increase the strength characteristics of weak foundations during the construction period. The main factors influencing functioning of a new natural-technical complex during construction on permafrost have been established, namely changes in the temperature field, loads of construction machines and physical and mechanical characteristics of soils. The study highlights feasibility of organising comprehensive assessments and mutual control of soil deformability using geotechnical monitoring and automated process control systems for machines and construction equipment. The technological regime for deep strengthening of weak foundations of geotechnical objects should include regulation of the parameters of construction loads and quality control of processes during vibration compaction of the upper zone and construction of a pile field. The article outlines the features of the experimental application of the complex technology to ensure the design bearing capacity of soils during reconstruction and construction of sections of the Northern Latitudinal Railway and Obskaya – Bovanenkovo railway.*

*Keywords:* *permafrost soils, subgrade, regulation, monitoring, bearing capacity, stability, technology.*

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## INTRODUCTION

The relevance of construction and reconstruction of transportation routes in the permafrost zone corresponds to the Strategy for development of the Arctic zone and ensuring national security for the period until 2035[1] and the main directions of socio-economic development of the Arctic. The authors of this article outlined in [1] the features of implementation of the Strategy.

The construction of geotechnical structures for transport infrastructure, especially subgrade on permafrost, is associated with the risk of their deformation and loss of strength not only during their operations, but also during the construction period. The experience of technological calculations and preparation of materials (regulations, maps and work plans) for work documentation for construction of sections of Tommot – Yakutsk, Bovanenkovo – Karskaya lines has shown the need to consider the risks of the state of incomplete main and protective structures. Already at the preparatory stage, the moss-turf cover is disturbed, surface water flows change, and in the main period, during distribution and movement of earth masses, the lithology of the massifs radically changes. This construction specificity is not fully considered in the standards and fundamental works of scientists on soil mechanics and subgrade [2–4]. At the same time, the Technical Regulations[2] indicate the need to ensure the strength and safety of buildings and structures at the design, construction and operational stages. The importance of managing the condition of objects throughout the entire life cycle is noted in the works [5; 6] and has been proven by construction practices [1]. When reconstructing the subgrade, one should additionally take into account the significant heterogeneity of the operations and the danger of degradation of the right-of-way[3].

The experience of technological design for development of transport infrastructure in Yakutia, Yamal and the Subpolar Arctic [7; 8] has shown that the greatest difficulty in constructing arises in areas of high-temperature permafrost.

The *objective* of the technological research is to develop methods for constructing subgrade on high-temperature permafrost soils that ensure safety and dependability of the structure by regulating and monitoring construction loads and impacts.

## RESULTS

### Methodology for Technical Regulation of Construction

Conditions for safe construction include its geotechnical monitoring (GTM), which, according to the standards[45,], includes control of temperature and humidity parameters in the body and base of an unfinished structure.

The main provisions of the relevant methodology are described by the authors in [9]. For stability of the foundation soils and stability of the structure at all stages of the evolution of the object, it is necessary to apply a technological regime for systematic regulation of construction and operational loads [10], which is provided by integrated technology (IT), patented and implemented on northern construction sites [11]. Its content is to organise geotechnical studies of the current state of soft soils and implement the highest safety-permissible vibration and shock loads from compaction machines. The composition of IT (Pic. 1) includes pre-construction (pre-production), the main construction period and structural blocks. The interaction of blocks and organisation of production management is carried out by the Centre of technical regulation (TR Centre). The main function of GTM (this is the fundamental difference with monitoring of already operating facilities) is information support and adjustment of production parameters.

For effective soil compaction, the requirement [4, 12] is accepted that loads must be applied to the soil's ultimate strength. The permissible technological load on soft soils must correspond to the condition:

$$K_r(F_s - F_p)t / F_t \geq K_{st}, \qquad (1)$$

where $K_r$, $K_{st}$ – accordingly, the design coefficients of reliability (dependability) and

[1] Decree of the President of the Russian Federation dated October 26, 2020, No. 645 «On the Strategy for development of the Arctic zone of the Russian Federation and ensuring national security for the period until 2035». [Electronic resource]: http://www.kremlin.ru/acts/bank/45972. Last accessed 15.12.2023.

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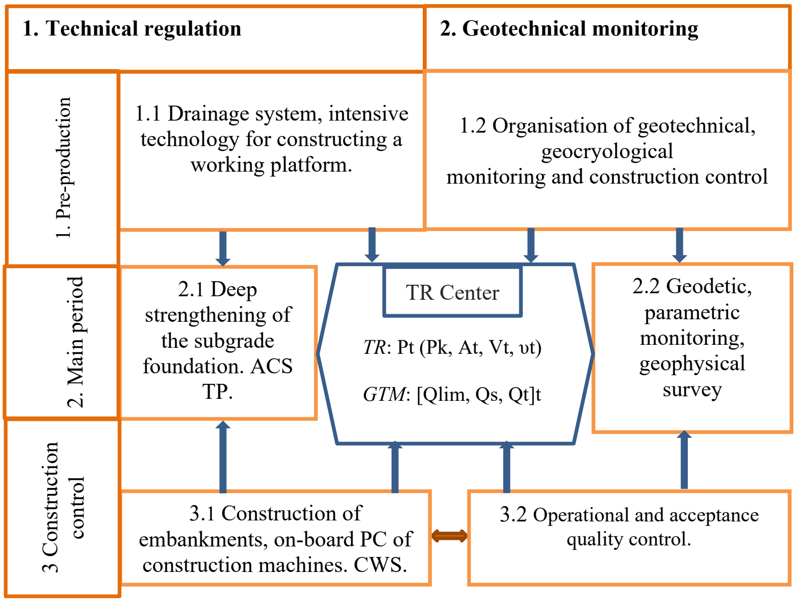
[4] SP [Construction rules] 25.13330.2020. Basements and foundations on permafrost soils. Moscow, 2020, 123 p.

[5] SP [Construction rules] 305.1325800.2017. Buildings and structures. Rules for geotechnical monitoring during construction. Moscow, Standartinform publ., 2017, 61 p.




***Pic. 1. Structure of technical regulation and monitoring of construction of geotechnical objects [developed by the authors].***

stability of the subgrade during the $t$-th technological cycle; $F_s$, $F_t$ – respectively, loads, safe for soft soils, and technological loads, $F_p$ – pore pressure.

The load $F_s$ is determined depending on the structure and strength characteristics of the soft layer according to the rules[4,6]. In the mode of vibration compaction of soils, the safe limit should be considered:

$$F_{\text{т}t}(P_k, A_t, V_t, \nu_t) < min[F_{lim}, F_s, F_{thix}]t, \qquad (2)$$

where $F_{\text{т}t}$ – load depending on the contact rigidity of the soil layer and the parameters of the vibrating drum which are weight $P_k$, amplitude A, speed of motion $V$, frequency υ;

$F_{lim}$ – soil strength limit;

$F_{thix}$ – thixotropic load limit in the $t$-th period of work (work shift).

Under these conditions, it is necessary to calculate the risk of violating the stability of the foundation by construction machines, when the technological impact exceeds the load that is safe for soils (taking into account pore pressure) [13]. The limit state is determined by the probability $P_t$ that the value $F_s$ will be less than the process load from the machines $F_m$ and the constructed part of the object $F_c$:

$$P_t = p[F_s - (F_m + F_c) / K_r]t < 0. \qquad (3)$$

Thus, during construction work, the TR Centre carries out continuous diagnostics of the subgrade been constructed to prevent its limiting state, especially in areas of individual design (slopes, karsts, etc.).

*The IT preparatory period* includes the stages of installing a drainage system, a working platform for heavy construction equipment and organising geotechnical monitoring. Drainage slots provide a reduction in humidity by squeezing water out of the active layer with a vibrating roller in the autumn at the beginning of freezing and migration of moisture accumulation [14]. Construction of a working platform, i.e., track for moving heavy construction equipment, is carried out in intensive compaction mode. At this stage, requirements for GTM are formed to determine temperature and humidity characteristics of soils, control the volume of water migration, total humidity and stability of the active layer.

To record current changes in heat exchange in the arrays of the object under construction and the natural environment according to the standards [5,6] it is necessary to carry out work on installation of stationary monitoring points and networks for monitoring the temperature regime and deformations of each layer. Regular querying of networks is especially important for assessing the performance of the drainage system and stabilisation of foundation soils.

During the pre-production stage, the TR Centre must have constant information about the condition of engineering structures. If stability

[6] SP [Construction rules] 447.1325800.2019. Railways in permafrost areas. Moscow, Standartinform publ., 2019, 40 p.

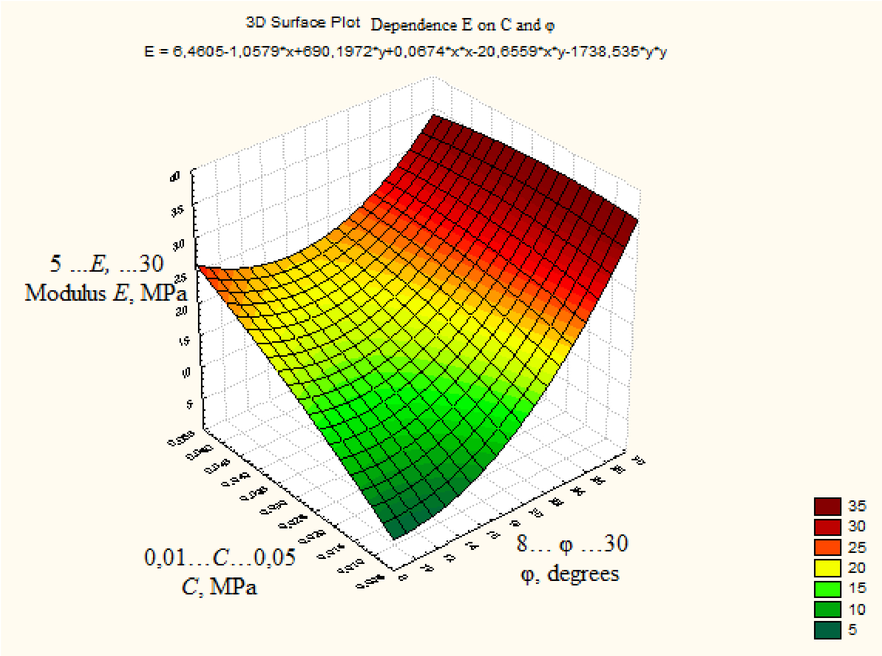



***Рис. 2. Relationship between changes in deformation modulus E, MPa, adhesion C, MPa and internal friction angle φ, degrees, of thawed cohesive soils [developed by the authors].***

according to the standards[4] is not ensured, organisational and technological solutions should be applied that include:

1) Intensive technology of vibration compaction of the foundation in combination with a drainage system of slots and drainage systems.

2) Replacing soft soil with sand, placing a sand mass on the mineral bottom.

3) Arrangement of a pile field.

The choice of hardening option includes modelling, calculation of technological parameters, forecast of settlement, strength characteristics of soils, timing and cost of work. When determining settlement during the construction period, it is necessary to consider anisotropy, the structure of soil strata, rheological properties of soils, the possibility of their deterioration if not stabilised during work and the production schedule. The deformability of the foundation of subgrade structures is predicted taking into account the principle of dynamic equilibrium between the amount of unfrozen water and ice content with changes in temperature and pressure [4; 6].

**Implementation**

The analysis of results of the study and experimental verification of IT and GTM is contained in the work of the authors [1] highlighting that «a comprehensive technology for construction of subgrade on high-temperature permafrost has been developed, based on the regulation of construction loads and monitoring of mechanical and thermophysical processes in real time».

The relationship between blocks of technical regulation and GTM is most evident during the main period of strengthening weak foundations. When removing soft soils and replacing them with sand, soil compaction is performed using vibratory rollers, shock-impulse or drill-and-blast technology. According to the requirements[4], main construction work must be accompanied by monitoring and regulation of the technological load, considering the forecast of the state of each layer during the work process [10].

To perform this complex task on a multi-kilometre section of the route with variable soil conditions, mobile mechanical division uses the entire range of GTM provided for by the standards[5] (geodetic, parametric monitoring, geophysical research) and the capabilities of the control and warning system [5, 15]. The characteristics of the foundation soils are checked by control drilling along the depth of the replaced soil mass to determine the presence of lenses, i.e., the remains of soft, waterlogged soils and peats. It is in these areas that increased humidity leads to a decrease in strength characteristics of deformation modulus (Pic. 2) and, as a consequence, to the risk of creep and squeezing out of soil from the under-slope part of the embankment. This phenomenon is confirmed by the regression dependence obtained from the results of statistical analysis of survey data on the experimental design section of Obskaya – Salekhard line [8]:

$$E = 6,46 + 690,19X + 0,07Y^2 - 1,06Y - 20,66XY - 1738,54X^2, \qquad (4)$$

where $X$ – adhesion C, MPa,

$Y$ – angle of internal friction φ, degrees;

E – deformation modulus, MPa.

This dependence ($R = 0,86; F = 27,9; p = 0; N = 48$) shows the interaction between the deformation and strength characteristics of soft soils. The use of drainage system technology and vibration compaction mode to prepare the working platform increases the values of characteristics $C$ and φ, and module $E$ increases accordingly.

The technological regime must consider the dynamics of pore pressure in the undrained (unconsolidated) state of the soil massif based on numerical modelling and assessment of the stress-strain state of the soil massif. If settlement has accelerated, the construction load should be adjusted, compaction should be stopped, and additional engineering and hydrological surveys should be carried out.

Experimental use of IT on foundations with deep (larger than the active zone) placement of subsidence soils according to the option of cutting them out and replacing them with sand showed the need for individual solutions described in [13]. For effective vibration compaction of sand, it is proposed to regulate the operating mode of the vibratory roller. When compacting a sand mass using the shock-pulse method [13], adjustable parameters are determined: placement of positions of the machine, impact impulse, number of impacts at each position. The peculiarity of regulation is the systematic diagnosis of the foundation at each position and in-between machine positions and calculation of the parameters of the impact (dynamic impact) depending on the state of the sand mass. The experience of constructing a highway on soft soils [11; 13] has shown the effectiveness of accompanying the work with comprehensive geophysical survey, including: electrical prospecting; seismic exploration; profiling by mobile ground-penetrating radar; hydrogeological surveys with regime wells. Integrated GTM makes it possible to control replacement of soft peat soils, pore pressure and density of the sand massif.

The most difficult conditions for the implementation of IT were revealed during development of the special technical specifications for completing construction (strengthening) of Nadym – Pangody railway [17]. According to engineering survey materials, the route had island permafrost, waterlogged fine silty sands and loams of fluid-plastic consistency, which are soft heaving soils with low bearing capacity. For reconstruction of the subgrade, fundamentally different transverse profiles were designed: a) an extension with berms to the embankment of the existing track; b) adding embankments over the existing track; c) new structures. The greatest deformations occur under technological loads during work in the under-slope part of existing track embankments with an increase in the thawing layer of plastically frozen soils. The risks of a dangerous combination of loads and the limiting state of an unfinished object are increasing, which are associated with variable conditions of a multi-kilometre long site, different design of structures, heterogeneity of soil composition along the longitudinal and transverse profiles of embankments and excavations. Under these conditions, it is necessary to calculate the risk of violating the stability of the foundation by construction machines, when the technological impact exceeds the load that is safe for the soil.

The design parameters must be determined taking into account the variable conditions along the route and during the work: heterogeneity of the characteristics of geology, lithology, and terrain slopes. Assessment of changes in the state of the right-of-way during construction of the subgrade is carried out by stationary monitoring points and the TR Centre using digital aerial photography and ground-based laser scanning data.

To increase the efficiency of geological and technical measures, recommendations are given in [1] on advisability of organising the constant transfer of digital information about the state of soils in each base layer based on the results of geophysical research to the TR Centre, to a unit of automated devices for regulating the modes of construction equipment. Intense machine loads can lead to intensification of hazardous natural phenomena. For example, landslide and karst-and-suffosion processes are sensitive to changes


https://static.ngs.ru

(movement) in the state of soil masses. Loss of stability of embankments can be caused by movement of earth masses on the track profile, redistribution of ground and surface water, and variable loads from earthmoving and transport machines.

Considering such interaction corresponds to modern trends in improving the mechanisation of work using a remote program or automatic technological processes' control system (ACS TP) [18]. Laser scanning systems consider the marks of the longitudinal and transverse profile of the structure, which change when machines operate at any point on the construction site. The operational task is to organise the interaction of geotechnical monitoring and automatic control systems of machines for a targeted and safe increase in the bearing capacity of foundations[7].

An increase in the vibration load of the roller in the active layer leads to an increase in humidity and, consequently, to a decrease in the deformation modulus of soils. Operational control should include synchronous assessment of compliance of current values of the safe load and regulated modes – changes in the amplitude and frequency of vibrations of the vibrating drum. Geotechnical monitoring data are the initial data for modern vibratory rollers [19]. The machine's on-board computer allows you to set the vibration parameters and speed of the roller depending on the degree of soil compaction. After registering and converting signals about fulfilment of the condition (1), it becomes possible to increase, or in case of a dangerous signal, immediately reduce the vibration load to the maximum permissible value and switch to oscillation. For example, the Variocontrol control system of the Bomag roller provides an infinitely variable amplitude increase and frequency adjustment to change the disturbing force to a maximum value. At the same time, the on-board PC determines the dynamic modulus of soil deformation through the ratio of the contact zone, dynamic pressure of the drum and the compressive strength of the soil. The current value of the machine's deformation modulus should be compared with the calculated deformation characteristics of the compacted layer obtained from GTM and soil laboratories. This data is transmitted to the TR Centre for diagnostics and forecast of the object's condition. Systematic regulation of vibration load and control of soil density makes it possible to increase strength and meet design requirements for the foundation at a specific site of embankment construction.

In areas of deep strengthening of weak foundations, it is necessary to organise quality control of the processes of vibration compaction of the upper zone for the working platform and installation of a pile field in the form of bored, geotextile or crushed stone piles (depending on the design solution) with a flexible grillage. For this purpose, modelling and calculation of the bearing capacity of piles are applied in the Midas GTS NX software [15; 17].

When constructing piles, based on engineering survey data, the geological structure, groundwater level and soil characteristics are considered. Modern vibratory hammers and drilling machines (for example, Liebherr series) ensure the quality

[7] ISO 18674–1:2015. Geotechnical investigation and testing – Geotechnical monitoring by field instrumentation – Part 1: General rules.

of work using an on-board ACS TP for monitoring and regulating the drilling speed, the depth and verticality of the auger immersion into the ground, and the pressure of the concrete mixture. The machine's software package allows obtaining a pile passport with its profile on the geological section and the volume of material laid in the well. During piling work, the control functions of GTM are aimed at clarifying information about the calculated values of soil resistance along the lateral surface of the piles. Testing of piles and of the interpile zone should be included in the work package to complete the technological cycle of foundation preparation.

The installation of piles using vibration loading and driving methods allows increasing the density of the foundation

$$\rho_{dt} = \frac{\rho_{do}}{1 - \frac{KcVdt}{V}}, \quad (5)$$

where $\rho_{do}$ – initial soil density,

$V$ – array volume,

$K_c$ – compaction factor;

$V_{dt}$ – additional volume of materials for strengthening the foundation during technical regulation (volume of sand during compaction of the drainage layer and volume of bored piles).

After piling work and installation of a flexible grillage, the final stage of IT is performed: vibration compaction of the grillage and control of the design dependability of the foundation for transition to the structural and technological cycle of embankment construction. When organising construction control, one should take into account the possibility of interaction between GTM and a modern control and warning system (CWS). Developed for operation of structures in difficult hydrogeological conditions, the CWS can be useful already at the construction stage for the purpose of timely identification of the pre-limit state, especially landslide areas. The block diagram (see Pic. 1) provides for interconnection of blocks with the hardware and linear subsystems of the CWS, which includes fibre-optic cables for measuring and monitoring temperature and strain by linearly distributed sensors [19]. The ability to obtain constant data about these characteristics will make it possible to control changes in the temperature field and stresses in soils during construction.

**Implementation Experience**

The practical application of the results of long-term studies has been described by the authors in [1]. Namely, it was noted that «The basic provisions of IT and geotechnical monitoring were developed and improved by the Institute of track, construction and structures of Russian University of Transport (MIIT) in 2009–2019. They served as a basis for development of technical regulations for construction of sections of Obskaya – Bovanenkovo – Karskaya and Berkakit – Tommot – Yakutsk railways and construction of Nadym – Salekhard highway [16]. The research was carried out within the framework of the «Agreement on Strategic Partnership between the Government of the Yamal-Nenets Autonomous District and Russian University of Transport», signed in 2013 and updated in 2018» [1].

Technical regulations for construction of sections of Obskaya – Bovanenkovo – Karskaya railway included monitoring that comprised an analysis of geocryological processes for construction of a technological motor road, one-stage and two-stage construction of embankments using near-route quarries. The forecast of formation of the thermal field under the design embankment of the Northern latitudinal railway section, carried out using the «Qfrost» program [11], taking into account thermal conductivity and the annual temperature balance, established the formation of new and development of existing blind talik zones.

The results of the authors' research on strengthening high-temperature permafrost soils were tested under the conditions of railway reconstruction. The proposals prepared for reconstruction of the subgrade have been included in the special technical specifications for design, construction and commissioning for «Completion of construction (strengthening) of Nadym – Pangody railway», and were reported at a conference organised by Yamal-Nenets Autonomous District [20].

## CONCLUSIONS

The construction of subgrade on high-temperature permafrost soils using powerful construction equipment is associated with the risk of attaining limit states of the foundation and loss of stability of unfinished geotechnical structures. The proposed IT includes a drainage device, adjustable technological modes and monitoring, which jointly and purposefully ensure the design requirements for safety of the facility.

Geotechnical monitoring at the stage of construction works and of regulation of construction loads includes complementary studies of mechanical and thermophysical processes occurring in layers of thawing and thawed soils during construction and assembly works. The linkage of monitoring functions with ACS TP of construction machines is promising to assess the impact of works on the condition of soils.

For effective implementation of the developed technological system for regulating and monitoring the processes of strengthening soft soils, it is advisable to provide in the consolidated calendar plan for construction of a section of the railway track the organisation of experimental sites of subgrade subject to field tests and geocryological studies of the dynamics of the bearing capacity of the foundation under the influence of construction equipment.

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