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Factors Influencing Development of Longitudinal Profile Deformations of the Roadbed in the Permafrost Zone

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ABSTRACT

Up to 2025 operations at the network of the Northern Railway (a subsidiary of JSC Russian Railways) may increase according to forecasts by 28,4 %, which is associated with construction of the Northern latitudinal railway. At the same time, a significant part of the Northern Railway is characterized by difficult climatic conditions: permafrost, polygonal-vein ice, peat bog areas, sharp temperature drops, significant amounts of precipitation in the form of snow. In the context of the planned increase in cargo intensity, the diagnostics of the roadbed in the zone of distribution of soils with weak bearing capacity against the backdrop of global climate change is of key character.

The article is devoted to survey of the roadbed located in the permafrost zone. The results of diagnostics of the state of the railway track make it possible to forecast the state of railway infrastructure facilities, to categorize subsidence of the roadbed according to the degree of danger, and to develop measures for its stabilization.

The objective of the work is to study the factors affecting degradation of the roadbed located in the permafrost zone.

The methods of the work are based on field examinations of «sick» places of the roadbed and statistical forms of analysis of longitudinal profile deformations (subsidence) of the track.

The result of this work is the study of influence of a number of factors on development of deformations of the roadbed located in the permafrost zone. In the future, it is planned, based on the results of diagnostics of the state of the railway track, to forecast the permafrost state of railway infrastructure facilities, to categorize subsidence of the roadbed according to the degree of danger, and to develop measures to stabilize it.

Keywords: railway, cryolithozone, moraine topography, thermokarst, seasonal thawing of soils, soil suffusion, profile irregularities, radarogram, track equal-elasticity.

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Background. In the future, up to 2025, an increase in cargo volumes by 28,4 % is forecasted at the Northern Railway operating ground. At the same time, the largest increase in transportation is expected in areas with diesel traction – 165,5 % of currently available volumes, which is associated with construction of the Northern latitudinal railway (Pic. 1). In the context of the planned increase in cargo intensity, the diagnostics of the roadbed in the zone of distribution of soils with weak bearing capacity against the backdrop of global climate change is of key character.

Vorkuta industrial region is located on the outskirts of the permafrost massif of Eurasia and belongs to the area of distribution of permafrost soils.

As a result of influence of various factors, both natural and technogenic in operation of linear structures (roadbed), longitudinal profile deformations (subsidence) of track arise, which contribute to additional development of longitudinal and transverse forces affecting both the running gear of rolling stock and railway track [1–5].

The *objective* of the work is to study the factors affecting degradation of the roadbed located in the permafrost zone.

The *methods* of the work are based on field examinations of «sick» places of the roadbed and statistical forms of analysis of longitudinal profile deformations (subsidence) of the track.

Results. Currently, considerable attention is paid to the technical state of the roadbed, quality of field examinations and analysis of the results of the work of diagnostic tools.

However, despite many statistical forms of analysis, each place of deformation is unique by the set and degree of influence of various factors, which can conditionally be divided into explicit and implicit ones.

So, when conducting field surveys of sites of longitudinal profile deformations, it is customary to consider as obvious factors: roadbed foundation flooding due to the lack of runoff of surface water, steepness of slopes of the roadbed and the absence of the roadside, sections with variable stiffness (for example, approaches to bridges)

Implicit factors include:

• features of the terrain, its folding, exposure and steepness of slopes, the transverse slope of the terrain, presence of through taliks;

• equal elasticity of track (different power of crushed stone, old crushed stonel, asbestos and sand ballasts, formed during repairs and straightening work);

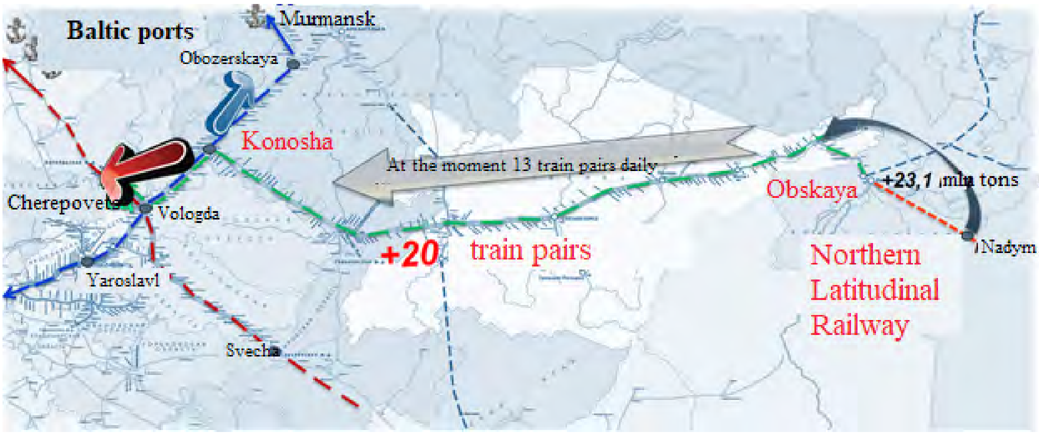
• accumulations of surface water located at the upper part of the embankment erected on the slope (suffusion of soils of the body of the embankment);

• violation of moss and peat cover and, as a result, vulnerability of «frozen» soils;

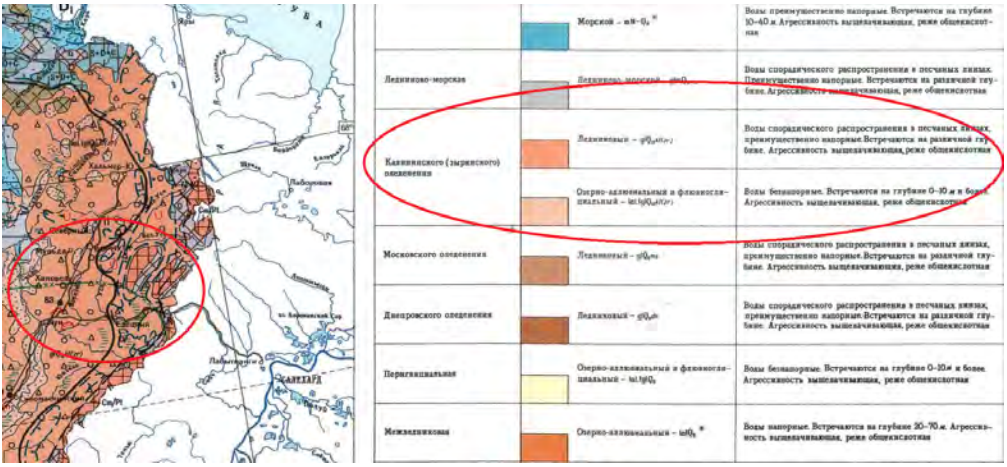
• soil humidity, water stagnation in various depressions, including in ditches for water drainage in the presence of dams in them;

• warming effect of snow in various special cases.

Before considering influence of implicit factors on deformability of the roadbed of the railway track, we pay attention to the geological history of the north of the territory of Komi Republic.



Pic. 1. Scheme for development of the Northern latitudinal railway and increase in train load (from the report of the First Deputy Head of the Northern Railway on the topic «Locomotive and locomotive crew work technology, development of the locomotive facilities following the development of the Northern latitudinal railway and approaches to the ports of the North-Western basin», Yaroslavl 31.08.2018).



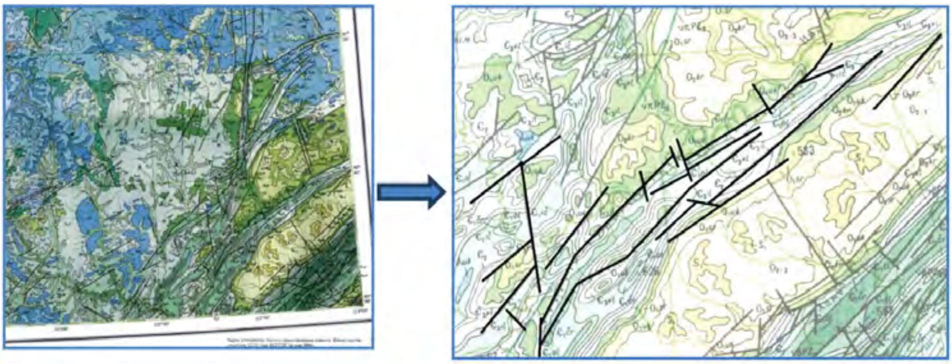
Pic. 2. Fragment of the view of schematic engineering-geological map of Vorkuta district of Komi Republic (Schematic engineering-geological map of Komi ASSR and Nenets national district of Arkhangelsk region, author Z. M. Dzenish, Ministry of Geology of the USSR, Ukhta territorial geological administration, 1966).

Pic. 3. A section of the railway track passing through the drumline relief (satellite imagery https://www.google.ru/maps/).

The rocks under consideration belong to formation of Zyryansk glaciation (hereinafter – ZG) [6–8]. The sediments of ZG region are represented by widely developed glacial formations (moraines), as well as water-glacial (sands, gravel) and lake-glacial (clays, sands) sediments, combined into Zyryansk super horizon of the Upper Pleistocene of the Quaternary system. Zyryansk moraines are composed of loams containing a large number of boulders. They contain sediments with marine microfauna trapped in ice from the Kara Sea shelf and coastal land. The moraine thickness is 30–50 m. Relict buried ice has been preserved in the glacial deposits of the Late Zyryansk glaciation.

In the subglacial region of ZG, alluvial-lacustrine and lacustrine (dammed) thin-layered ribbon clays, sandy loams, and sands with plant debris are common.

Hydrogeological characteristics of water: for the glacial complex – sporadic (single, separate) distribution in sandy lenses, mainly pressure lenses, occur at different depths, it is of leaching aggressiveness, less commonly acidic; for lacustrine-alluvial water, pressureless water is found at a depth of 0–10 m and more, it is of leaching aggressiveness, less commonly acidic [6; 9].



Pic. 4. A fragment of the state geological map and «Lineamenta» layer in GIS (Internet resource «Karpinsky All-Russian Scientific Research Geological Institute». [Electronic resouce]: http://www.geolkarta.ru/).

The moraine relief (hilly-ridge, hilly-lowland), as well as the Drumlin relief, which represents elongated hills consisting of deposited moraine material, measuring 900–2000 m in length, 180–460 m in width and 15–45 m in height (Pic. 3) is typical for ZG.

Relief influence. Railway track based on the conditions of minimal volumes of earthworks, as a rule, passes along the flood-lands sections of rivers.

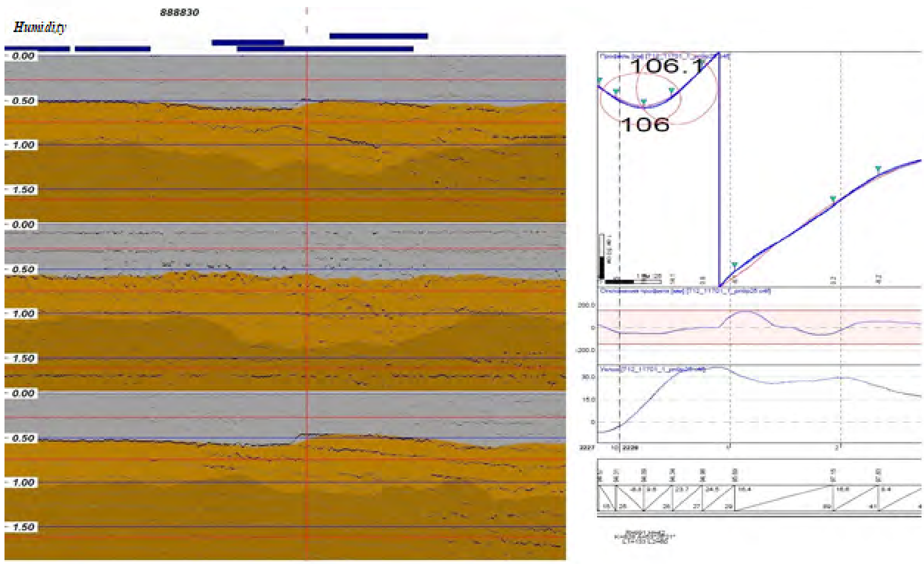
So, Pic. 3 shows a section of Konosha–Vorkuta railway line. The predominant deviation of the terrain is towards the floodplain of the Vorkuta River, where the track passes through its ancient high terraces. In accordance with existing standards for designing culverts, there is no culvert (in the area under consideration), however, as a result of water flow accumulating in the places of folds of the drumlin (partially polygonal) relief and development of thermokarst, lakes are formed that are directly adjacent to the body of the embankment. As a result, waterlogging of the soil base of the roadbed occurs. In the presence of a significant transverse slope of the terrain, a slow filtration of water through the body of the embankment (accompanied by soil suffusion) occurs.

However, the volume of water runoff is not always sufficient in such places for formation of lakes, in most cases when the railway crosses the ravines, where the roadbed is represented by high embankments of 6–12 meters or more, there is no visually distinguishable accumulation of water. The described irregularities in the terrain, as a rule, are heavily overgrown with stunted vegetation (dwarf), which has a warming effect on the state of «frozen» rocks in these places (we will conditionally call them «lineoments», Pic. 4).

In combination with a significant thickness of the Quaternary sediments, which can reach 100 meters in the area under consideration, development of open taliks is observed, as a result, the soils in the base of the body of high embankments are both in a thawed and extremely waterlogged state. This was clearly confirmed when arranging intersections of the track and the gas pipeline in 2010–2011, when a water horizon was opened at the base of the embankment in winter. A significant part of the longitudinal profile deformations located in the region under consideration passes through similar sections of the relief.

Track equal elasticity. During operation of the railway track in places of constant deformation, work is carried out on its mechanized straightening. As a result of long-term operation and numerous «elevations», the upper part of the embankment has a layered structure, which is presented from bottom to top by: main soils of the embankment body, then a layer of old sand and gravel ballast, old asbestos ballast and the upper part with a layer of clean ballast. If the bulldozer cuts evenly over the top layer of contaminated crushed stone (during the course of track repair), a layer of old compacted asbestos (which can be tactilely compared with asphalt) is exposed. With a mechanized straightening of sediment (hollows) of the track, the layered structure is broken.

Modern track-examination systems allow georadar sounding and profiling of deformative sites of the roadbed. The methods of interpreting georadar profiling data and shallow seismic tomography developed at Far Eastern State Transport University (FESTU) [2–3] make it possible to obtain a multilayer model of the deep section of the roadbed and foundation

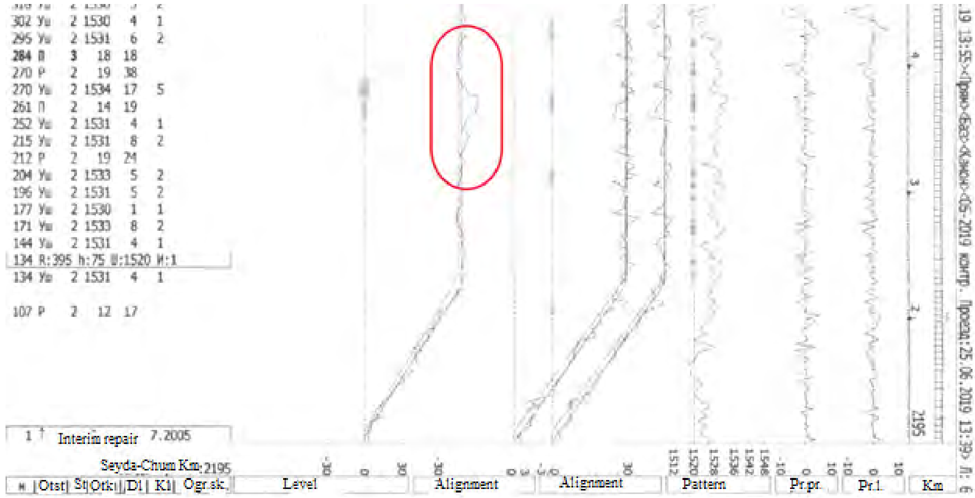


Pic. 5. Radarogram of soils, combined with marking of the longitudinal profile of the track (overhaul in 2009).

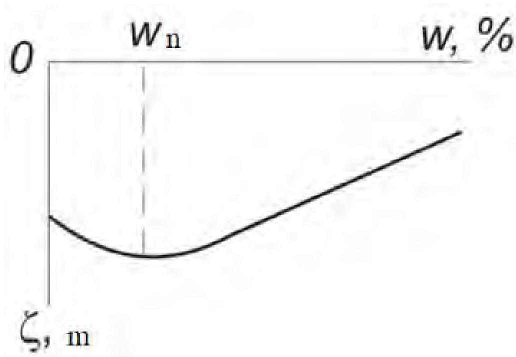
Pic. 6. Data from the video camera of PS067 track-measuring car (from the archive of Vorkuta Track Division of the Northern Directorate of Infrastructure, video file of the surveillance camera of PS067 track-measuring car, June 2019).

with a continuous distribution of strength and deformation characteristics of soils [12], identified by areas of heterogeneity both in transverse profiles and in volumetric design.

Pic. 5 shows a radarogram of soils (data from DCS Integral) [13], combined with marking of the longitudinal profile of the track section (overhaul of 2009). In the left part of the picture (radiogram) along the track axis and the left roadside, local penetration of old asbestos ballast into the layer of the main soils of the body of the embankment is observed. The blue stripes in the upper part of georadar sounding indicate a waterlogged state of the soil. The occurrence of soils in the transverse plane is uneven. On the right side of Pic. 5, this



Pic. 7. Graphical chart of the track-measuring (geometry) car (from the archive of Vorkuta Track Division of the Northern Directorate of Infrastructure, graphical chart of the track-measuring car PS067, June 2019).



Pic. 8. Change in the depth of seasonal freezing and thawing depending on soil humidity [based on [9], A. V. Boytsov].

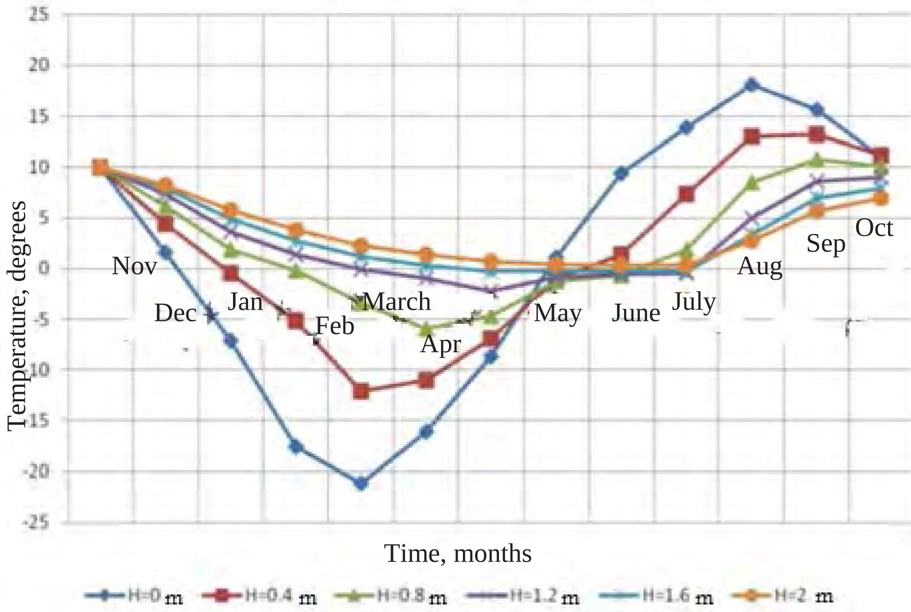
section is represented by marking of the longitudinal profile (TsNII-4 data) [14], where it is possible to observe the longitudinal profile deformation of a track with a length of 120 m and a deformation value of 0,250 m.

Implicit factors (contributing to occurrence of longitudinal profile deformations of embankments erected on the slope) include the presence of depressions filled with water and located at the upper part of the embankment (suffusion of the soil body of the embankment). In this regard, special attention when conducting field surveys of the embankment when it is located on a slope should be given to the presence of catchment basins directly adjacent to its body (Pic. 6).

As a result of the water arm being formed, soil suffusion (removal of small soil particles) occurs, which can lead to sudden deformation of the roadbed, or subsidence of one or both rail lines of different intensity [9; 11]. So, in June 2019, on the 2195th kilometer of Seyda–Chum haul, intensive subsidence of the right rail line was observed (Pic. 7), which entailed a limitation of speed of trains: on the first day to 25 km/h, and on the next three days – up to 40 km/h.

Humidity. The thermal conductivity coefficient of dispersed rocks increases with increasing humidity, since the thermal conductivity of water and ice is higher than that of air. Thus, depth of freezing-thawing of rocks with increasing humidity will decrease [8; 10]. The general dependence of changes in the depth of seasonal freezing and thawing of rocks on their humidity content is presented in Pic. 8.

The initial part of the graph shows a slight increase in the depth of seasonal freezing and thawing with an increase in humidity from 0 to



Pic. 9. Monthly temperature distribution at a depth of H1 = 0 m; H2 = 0,4 m; H3 = 0,8 m; H4 =1,2 m; H5 = 1,6 m; H6 = 2,0 m [based on [10], S. A. Kudryavtsev, A. V. Kazharsky].

a certain value of *Wnz*. In this interval, humidity does not freeze at a negative temperature and the rocks remain unfrozen (chilled). With increasing humidity above *Wnz*, the proportion of phase transitions in the total heat circulation of the rock increases, and the depth of their freezing and thawing decreases.

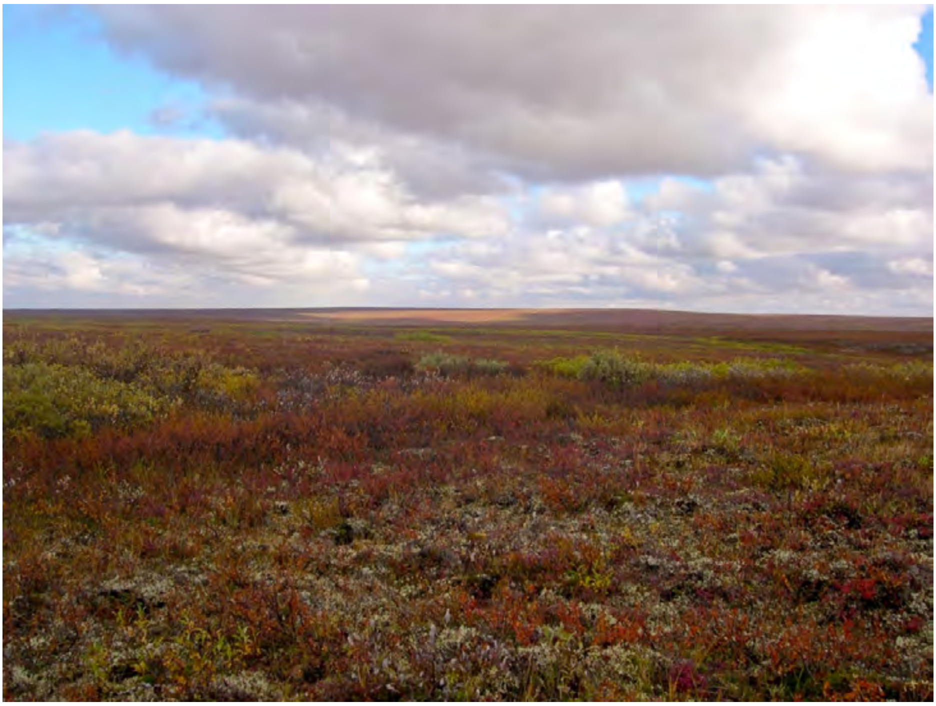
Of great importance in formation of the thickness of the layer of seasonal freezing (or thawing) is the temperature shift, which is the temperature difference between the surface of the rocks and the base of the seasonally freezing (thawing) layer. Thermal shift occurs due to an increase in thermal conductivity of rocks during their transition from a thawed to frozen state; the greater is ice content of frozen rocks, the greater is the difference in thermal conductivity coefficients. This phenomenon is explained by the fact that the thermal conductivity of ice is about four times higher than the thermal conductivity of water. It was also noted that the more dispersed is the rock (at the same humidity), the lower is the thermal conductivity coefficient and the smaller $\lambda m/\lambda t$ ratio.

Lowering the average annual temperature of the rocks at the bottom of the seasonal thawing layer leads to a decrease in the depth of seasonal thawing of rocks, which is confirmed by the research data of the FESTU [10], Pic. 9.

On the gentle drained slopes and watersheds, in the aeration zone, composed of fine and medium-sized sands, at the beginning of intensive soil freezing, the amount of humidity is close to the value of the maximum molecular moisture capacity and does not exceed 4–5 % of the rock volume. In the summer season, especially during the period of snowmelt infiltration, soil humidity content increases by 2–3 times, in accordance with this, the thermal conductivity coefficient sharply increases with a constant value of phase transitions. This phenomenon leads, firstly, to rapid thawing of the upper part of the geological section and, secondly, to formation of a positive temperature shift at the bottom of the active layer [7].

Quantitative assessment of deformation of dusty loam of a refractory texture associated with frost heaving and thawing given in [10] showed that for a one-year cycle at a groundwater level of 1 to 2,5 m from the day surface, humidity increases by 68 %, and the resistance to shift of clay soil is reduced by five times.

Mosses and peat bogs. It is difficult to imagine Bolshezemelsky tundra without mosses, lichens and peat bogs. However, their influence on the state of «frozen» soils is underestimated. During the technogenic impact in the right of way of railway lands (work of earthmoving equipment, all-terrain roads),



Pic. 10. Moss cover of the Bolshezemelsky tundra (photo by V. V. Shapran, 2018).

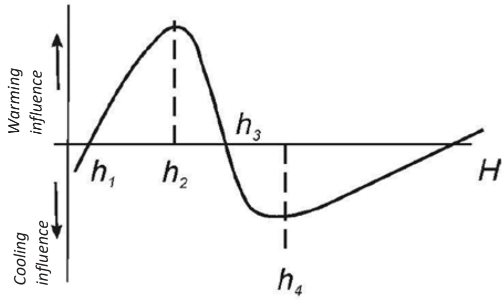
vegetation cover is disturbed. Recultivation works in most cases are not carried out, when developing trenches for various purposes, their strengthening and warming of their cross-section are not performed.

So the frozen strata and vegetation, developing in time, react to changing of each other. Plant communities in many cases are good indicators of thermal and humidity conditions of the soil, and this circumstance is widely used in permafrost surveys. Often, destruction of vegetation leads to an increase in summer temperatures of rocks and the depth of seasonal thawing, which contributes to strengthening of cryogenic processes, primarily thermokarst, thermoerosion and waterlogging. Violation of the thermal regime of the soil of the base of the body of the embankment leads to its deformations.

Among the soil covers, the cooling role of wet mosses is especially high (Pic. 10). The fact is that in the thawed state, the thermal conductivity coefficient of moss is several times less than in frozen state. Therefore, in winter, under such a cover, the soils cool off quite intensively, and in the summer they warm up slightly. Moss covers with a thickness of 15–20 cm lead to a reduction in the depth of seasonal thawing by a factor of 2–3 compared with the exposed surface and to a few degrees lower average annual temperature of the rocks [6; 9].

The peat cover behaves in a similar manner. The thermal conductivity coefficient of peat in the thawed state, as a rule, is two times lower than in the frozen one. Under a certain humid regime of the peat bog, the difference in thermal conductivities can differ significantly. Therefore, even with an average annual positive temperature on the surface of peat, underlying soils can be in a frozen state [9].

Snow. Snow cover is formed almost everywhere in areas where frozen rocks are found. Its influence on the radiation-thermal balance of the surface is very large and diverse. First of all, snow increases the albedo of the surface, increasing its reflectivity several times. This leads to a decrease in absorption of radiant energy, and to a decrease in the average annual temperature of the rocks. In addition, a significant reduction in the incoming part of the heat balance is caused by heat consumption for melting snow and partial evaporation of melt water. Melting snow maintains a zero temperature on the surface for some time, which prevents the soil from warming up despite the positive air



Pic. 11. Change in the effect of snow cover on the temperature regime of underlying rocks depending on its thickness [[9], A. V. Boytsov].

Pic. 12. Cutting of a snow hole using a FRES machine (photo by V. V. Shapran, 2015).

temperature. From here follows the cooling effect of the snow cover. At the same time, snow cover, which has low thermal conductivity, as a heat insulator, protects the soil from winter heat loss and acts as an insulating factor. The higher are heat-insulating properties of snow in winter, the greater is its warming effect on the soil. Thus, the main factors determining influence of snow cover on the surface temperature are the high albedo and the heat-insulating role of snow.

Study of the effect of snow cover on the temperature regime of underlying rocks depending on its thickness, the results of which are shown in Pic. 11, showed that if snow has a low power (up to h_1), then its role as a reflector of sunlight predominates, and such a low-power cover has a cooling effect on soils. As the thickness of the snow cover increases from h_1 to h_2, its warming effect prevails. With a further increase in snow thickness from h_2 to h_2, a large amount of heat is spent on its melting in the spring, which lasts a considerable time at a positive air temperature. Therefore, the warming role of the snow cover is gradually decreasing and, ultimately, it becomes a cooling factor for rocks (from h_3 to h_4), which is most evident in areas where snow does not have time to melt in the warm season. Further accumulation of snow leads to formation of perennial snowfields, the temperature regime on the sole of which depends on various environmental factors, including the influx of deep heat [9; 11].

In general, for regions where permafrost strata are developed or stable seasonal freezing of soils is observed, snow cover is an insulating factor. In the field of seasonal freezing with removal or absence of snow cover, a significant increase in the depth of winter freezing of rocks is observed. In the area of permafrost distribution in the presence of merging permafrost, a decrease in snow thickness leads, on the one hand, to a decrease in the average annual temperature of the rocks, and, consequently, to a certain decrease in thawing depth, and, on the other hand, to an increase in the amplitude of fluctuations in the temperature of the rock surface, and therefore – to increase in this depth.

Thus, removal or absence of snow cover does little to change in summer heat exchange in soils, which mainly determines the depth of their thawing. According to field observations, it was found that an increase in the thickness of the snow cover by 5–15 cm leads to an increase in the average annual temperature of the rocks by 1°C. Therefore, with sufficient snow cover, rocks can have a positive temperature in areas where low average annual air temperatures are observed. This problem is most relevant for the region under consideration, where a constant thick snow cover is observed from October to May. The roadbed is represented by high embankments passing through open tundra territories, this fact contributes to accumulation of significant amounts of snow. In some cases, the embankments are completely covered with snow and «snow holes» are formed (Pic. 12).

Conclusion. Summing up, we can say that the railway has become an integral part of the ecosystem of the Arctic region. The tundra itself is a unique zone of nature, which is characterized by the presence of permafrost, soil flooding by river waters during the flood period and the complete absence of woody vegetation, which creates certain difficulties in operation of the infrastructure.

The analysis of many factors that influence the occurrence and development of deformations along the roadbed that lies in the permafrost zone showed that each place of deformation should be considered and studied individually. It is sometimes difficult to determine the key factor that has the maximum impact on development of deviations from the many factors identified. The results of the analysis should be compiled into a catalog for further categorization of deformations.

In the future, it is planned, based on the results of diagnostics of the condition of the railway track, to forecast the permafrost state of railway infrastructure facilities, to categorize subsidence of the roadbed according to the degree of danger, and to develop measures to stabilize it.

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