Technogenic Hazards of Russian North Railway

Isaev Vladislav, Kotov Pavel and Sergeev Dmitrii

Abstract The degradation of permafrost can induce geohazards such as thaw subsidence affecting the performance of railway infrastructures. For example, along an 800-m-long segment Russian North Railway (from Pesets to Hanovey railway station), some zones of thaw subsidence were studied in summer 2018. The subsidence can be as high as 0.5 m. Drilling, landscape zoning, near-field transient electromagnetic sounding, and electrical resistivity tomography were carried out to assess the underlying stratigraphy and permafrost conditions. Engineering and geological conditions of the site are complicated by the presence of permafrost. Soils can be in thawed and frozen state at the base of the embankment. The spatial arrangement of thawed and frozen soils is discontinuous. The thaw settlement is due to the snow accumulation along the road embankment which insulates the ground surface in winter and prevents further ground freezing.

Keywords Russian North Railway · Technogenic hazards · Hanovey

1 Introduction

Spurred by recent concerns over rising transportation costs and the desire for increased accessibility for natural resource development, several cold climate railroad projects are currently under development around the globe. As demand for new cold climate railroads grows, stability of railway transportation structures over permafrost becomes an important challenge.

The construction of transportation infrastructure in cold climates has always been a challenging task. The history of creation of railways in permafrost regions is already more than 110 years: Transbaikalian, Amur, Alaska, Qinghai–Tibet Railway, Gudson, Labrador, Baikal–Amur (BAM), Yamal, and some other railways in Russia,

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A. Petriaev and A. Konon (eds.), *Transportation Soil Engineering in Cold Regions, Volume 1*, Lecture Notes in Civil Engineering 49,
https://doi.org/10.1007/978-981-15-0450-1_32

USA, and Canada. Construction of each of these roads is an outstanding stage of transport construction and attempt to solve the main problem: to provide stability of a subgrade on sites of a permafrost and deep seasonal freezing of the soils [5]. Compared to other Arctic countries, Russia has the most developed railway infrastructure located in the permafrost area. But annual emergency repair operations on railways in the permafrost continue to be carried out.

Northern transportation infrastructure is sensitive to permafrost degradation [4, 5]. Thawing of ground ice and thaw consolidation promote embankment subsidence and depressions in the road pavement [3, 8]. Permafrost warming can be amplified by construction operations (e.g., soil compaction, destruction of the vegetation cover), embankment geometry, snow accumulation on side slopes, or changes in material properties, such as the normally low albedo of pavement surfaces [3, 5, 8]. Permafrost degradation presents problems due to the high costs of construction and maintenance and because driving conditions may become hazardous.

However, each territory has its own characteristics that must be considered. Therefore, a long-term study showed the significant deformations of the track that were observed along a part of Russian North Railway. This is a very difficult section where repairs often take place and embankment deformations observe. In the previous time, the intensive settlements were observed in 1953, 1959, 1966, 1968, and 1973. In 2009, a major overhaul of the track was carried out on this section using old-fashioned materials, and slight settlement was observed in 2010. In the spring of 2014, a significant increase settlement (0.5 m) was observed. After that, settlement was eliminated in 2015 and 2017. Now, the settlement tends to further development (Fig. 1). The cause of the deformations was studied in the framework of joint work between Russian and Norwegian researchers (project "Russian-Norwegian Research-based education in Cold Regions Engineering").

Fig. 1 Thaw settlement in Hanovey site

2 Study Site

The surveyed section of the Konosha–Vorkuta line is located beyond the Arctic Circle in the extreme northeast of the Komi Republic in the Bolshezemelskaya tundra; administratively, the survey site is part of the Vorkuta region. Along the line segment from the Pesets to Hanovey railway station railway line runs along the right bank of the River Vorkuta (Fig. 2).

Hanovey is located 31 km from the city of Vorkuta (67° 16′ 58″N, 63° 39′ 06″E) on the bank of the Vorkuta River. It was founded in 1948 on June 21, 1949. Population of Hanovey was 3,134 people in 1959 and only 4 people in 2011.

In landscape terms, the site is characterized by the spread of peaty-bumpy tundra, which is a system of micro-depressions, hollows interspersed with hillocks and permafrost. Mosses, lichens, and ernik (dwarf birch) grow on the hillocks. Slides and hollows, along which surface runoff is periodically carried out, are overgrown with shrub of polar willow, dwarf birch, and sedge grass vegetation.

A characteristic feature of the climate is a long cold winter (from October to May inclusive), followed by a short and cool summer (about 2 months—July and August). The average annual air temperature is −6 °C, the average temperature of the coldest month (January) is −20.3 °C, and the average air temperature of the warmest month (July) is +9.5 °C. The absolute minimum air temperature is −52 °C, and the absolute

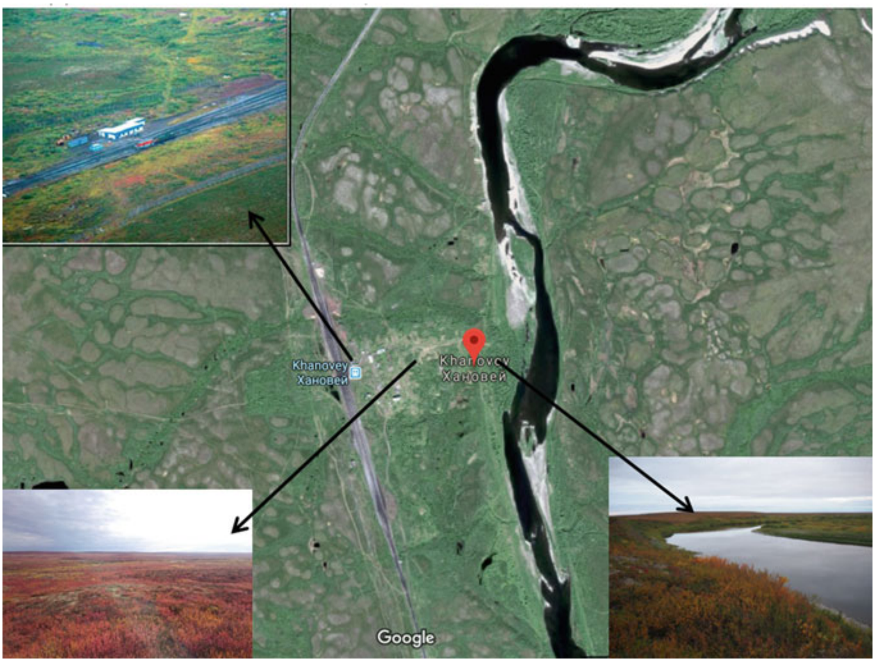

Fig. 2 Location study site

maximum air temperature is +31 °C. The average annual precipitation is 456 mm. It is distributed unevenly: 60% of the annual amount of precipitation falls in the form of rain in a short summer–autumn period. The predominant wind direction in winter is southwest; in the summer time, the northern winds dominate. The average annual wind speed is 4.1 m/s. Winter southwest winds create large snowdrifts. According to long-term data, the maximum thickness of the snow cover reaches 1.2 m in the tundra.

The surveyed area is characterized by continuous evolution from the surface of Quaternary sediments, lying on Permian bedrocks. Quaternary stratum is represented by modern alluvial and moraine deposits at an open depth of up to 5 m. The cover sediments are represented by loam and silt (PrQ-iv) of yellow-brown color. They are the basement of the railway embankment throughout the surveyed area.

3 Methods and Results

3.1 A Temperatures, Permafrost Table, and Thaw Depth

Ground temperatures were measured with using 6-thermistor set that was installed in 2015 in a three 6-m-depth boreholes drilled on the western side of the road. Temperatures were measured with an accuracy of 0.1 °C between −10 and 10 °C and an accuracy of 0.2 °C through the rest of the operating range (−50 to +30 °C). Data were recorded every 24 h from October 2015 to October 2018 by a HOBO U12 logger. The average annual temperature of soil in two boreholes was −0.2 … −0.5 °C, and + 0.8 °C in the third one. All temperature data were submitted in international GTN-P database [1].

Thaw depth was measured in 2016–2018 following CALM method. Measurements along embankment provided data on annual thaw patterns and identified the factors responsible for active-layer variability. Probing of the active layer is performed mechanically with a graduated metal rod. The map of the seasonal of thaw depth distribution was built after data processing (Fig. 3) Maximum depth is 1.85 m, and minimum is 0.35 m.

3.2 Geophysical Research

Near-field transient electromagnetic sounding (NTES). Soundings are made by passing a current through a large, square transmitter loop. The current flow generates a steady magnetic field. Abruptly shutting off the current flow disrupts the magnetic field and induces a circulating current system in the ground below the transmitter loop. The diffusion of these induced currents is controlled by the electrical conductivity of the ground. The current attenuation is small in conductive regions, and the current

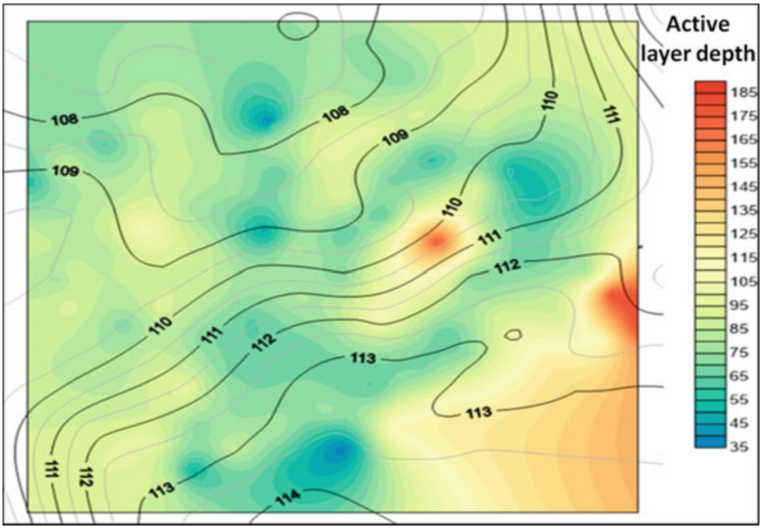

Fig. 3 Map of the seasonal of thaw depth distribution (cm)

passes slowly through them. Resistive regions (with low conductivity), on the other hand, attenuate the current flow. Current traverses these regions more rapidly than in conductive regions. The circulating induced currents produce a secondary magnetic field that is sensed by a receiver coil located at the center of the transmitter loop. Because of the relationship of the electrical conductivity structure of the ground, the current diffusion, and the secondary magnetic field, the voltage recorded by the receiver can be used to estimate the ground conductivity. The result is that the measured voltage–time curves, or transients, can be converted into resistivity-depth functions by a nonlinear parameter estimation process called inversion [2].

The equipment used was described above. Two transmitters were used for the measurements: a battery-powered transmitter and a generator-powered transmitter for deeper exploration. Square transmitter loops were used with nominal side lengths of 50 m.

Using this method allowed to determine the thickness of permafrost (Fig. 4). Frozen soils have great resistance (red zone). Thus, the thickness of permafrost in this area is 40–95 m. But the resolution of this method is small for active layer depth.

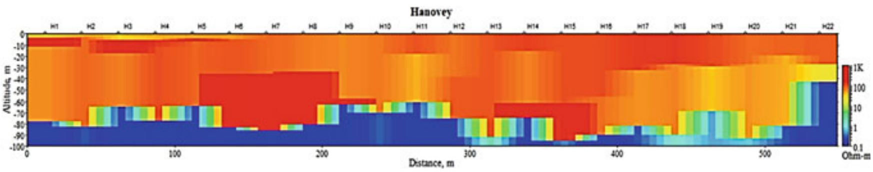

Fig. 4 Geoelectric cross section NTES

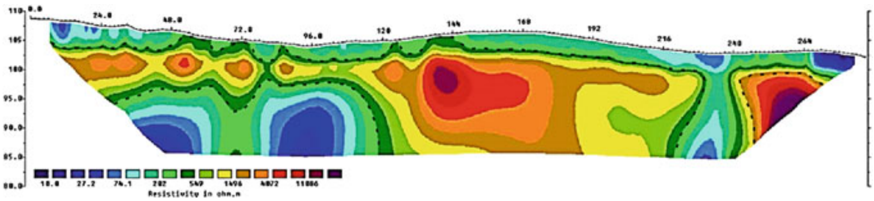

Fig. 5 Model of electrical resistivity

Electrical resistivity tomography (ERT). Among the available near-surface geophysical methods, electrical resistivity tomography is a powerful tool for permafrost investigation because the electrical resistivity of a medium is highly sensitive to the transition from unfrozen to frozen state. An ERT was carried out along road embankment to assess the permafrost conditions. Values of apparent electrical resistivity were measured using multi-electrode installations Scala-64. The four electrodes were aligned along the survey line. The direct injection of electrical current between the two outer electrodes induced electrical potential measured between the two inner electrodes. The array with a 2-m spacing between the electrodes was first moved at 2-m interval along the survey line. The spacing was then increased to 4 m, and the array was moved again at the same interval along the survey line. A 2-dimensional data set of apparent electrical resistivity was thus obtained through the variations in depth of investigation according to the increase in array length and moving center points along the survey line. Because the road embankment was too stiff, it was not feasible to drive the electrodes into the gravel pad and carry out an ERT for the investigation of the embankment and underlying ground.

The data set of apparent electrical resistivity was then inverted using the software packages to produce a model of electrical resistivity (Fig. 5). This inversion algorithm is based on the smoothness—constrained least-squares method taking into account the topography along the survey line minimized the difference between the predicted and measured values of apparent electrical resistivity by adjusting the electrical resistivity of each block making of the model. The result is an uneven distribution of thawed and frozen zones around the embankment.

3.3 Geological Structure

Three boreholes and two test pit (for high and low embankments) were made to study the geological structure and properties of soils. The results are shown in Fig. 6. The underlying layers are represented by loam and silt with different ice content.

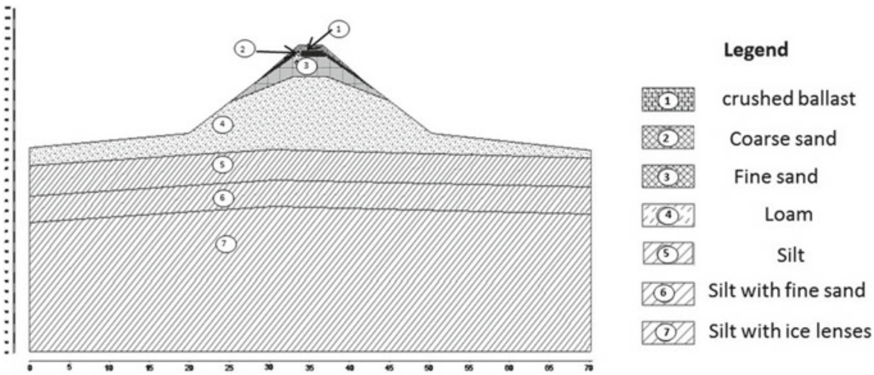

Fig. 6 Geological structure

4 Discussion

Permafrost terrain is ground that remains below 0 °C year around. The definition is based on the thermal state of the soil. Permafrost ground can be considered perennially frozen with a thin surface "active" layer that thaws each summer. The frozen ground has variable proportions of ground ice commonly well in excess of the water retained in the soil following first-time thaw. When thaw does occur, the excess water is expelled and consolidation produces substantial settlements [6, 7]. The thermal stability of the frozen ground is sensitive to minor changes in heat transfer at the ground surface. Changes in surface properties such as stripping vegetation or changes to moisture retention capacity of the soil can alter the surface heat balance, initiating thaw and increased active layer thickness. These conditions are challenging for highway engineers particularly in the southern fringe of permafrost where the ground temperature is between −1 and 0 °C. Any change in ground-air heat flux can initiate the retrogressive thaw that can result in large embankment settlements. Railroad led to a significant change in permafrost conditions at the test site (Fig. 7). It is shown on map that temperature increases at embankment. There was a thawing of permafrost and the formation of a thawed layer that does not freeze in winter.

Moreover, the thick road embankment disrupts the gentle topography and acts as a barrier favoring the snow accumulation. The thawing of permafrost is therefore the snow accumulation along the embankment shoulders which insulates the ground surface in winter and prevents further ground freezing. Engineering and geological conditions of the site are complicated by the presence of permafrost. Soils can be in thawed and frozen state at the base of the embankment. The spatial arrangement of thawed and frozen soils is sporadic.

Such condition is a great challenge to geocryological survey. The question is producing the correct and full description of permafrost state and permafrost dynamics. Usually, the investigators use the ground temperature and active layer depth as universal indicators of permafrost reaction to external disturbances as climate change or

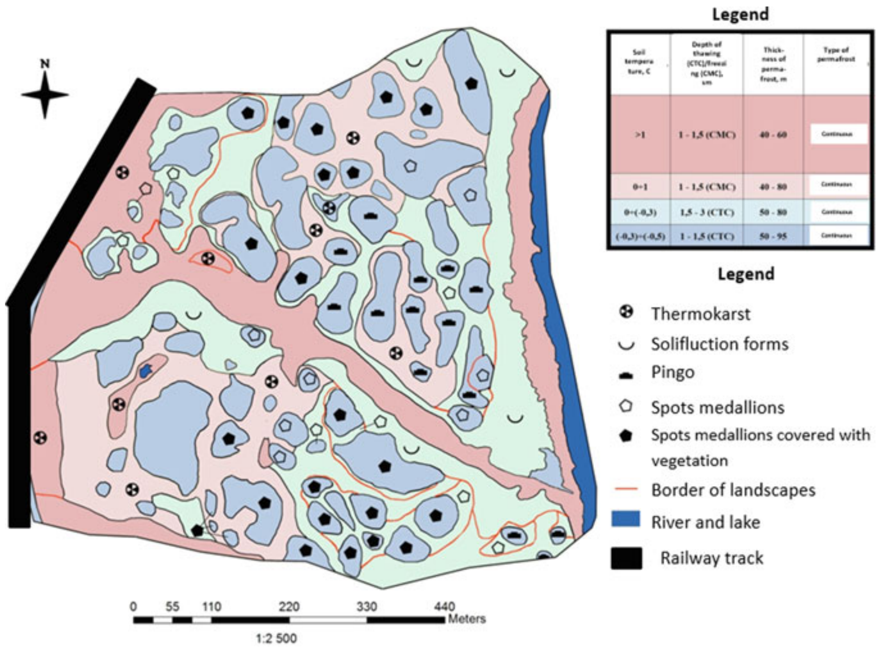

Fig. 7 Map of geocryological conditions of the Hanovey area

anthropogenic influence. For example, in our case, the average annual temperature of the soil on the sole of seasonal thawing within different landscapes is slightly different. This temperature is −0.3 to −0.5 °C and practically does not change from year to year. This is associated with significant heat expenditure on phase transitions. Thus, under these conditions, temperature monitoring becomes little informative.

On the other hand, the maximum thawing depth is also not convenient as a universal indicator. Measurements of maximum thawing at the end of the warm period provide information only on the position of the permafrost table. The dynamics of this situation may depend on many factors and sometimes show the opposite dynamics. In other words, against the background of warming, this depth can be reduced.

And here, the combination of research methods takes on a special significance. Thermometric observations in boreholes allow us to calibrate numerical models and also find the landscapes with no seasonal ground freezing in winter. Geophysical observations allow to outline the talik zones in the plan and in the section. Measurements of the depth of seasonal thawing allow you to select areas with shallow thawing, which often correspond to peaty ice-bounded grounds.

This allows us to understand the state and dynamics of permafrost, which determines the composition and activity of hazardous processes. In particular, areas of residual thaw layer indicate the process of permafrost degradation from the top. The shallow depth of thawing and the high apparent electrical resistance of soils indicate the danger of the near start of the thermokarst process. The presence of a deep talik zone makes senseless the protection of permafrost from further thawing.

5 Conclusions

While the road is still suitable for traffic despite the major thaw subsidence, the only economically viable mitigation of thawing of permafrost is to allow free the thaw settlement and reload the road embankment when needed until stabilization is attained. The monitoring of subsidence is recommended to assess the rate of thaw settlement. Other geophysical investigation and deep sampling would provide the clay unit thickness and undisturbed frozen samples to carry out thaw consolidation test. These data could be then integrated in a numerical simulation of the thermal regime and consolidation behavior of permafrost. The assessment of the vulnerability to thawing of permafrost is fundamental to maintain this critical access to Vorkuta.

Acknowledgements This research was supported by Norwegian Center for International Cooperation in Education ("Russian-Norwegian research-based education in cold regions engineering"). Special thanks to master's students of Lomonosov Moscow State University and Norwegian University of Science and Technology for assistance in field research. Also thanks to Scientific program #51 of the Presidium of Russian Academy of Science.

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