Influence of hydrogeological and hydrological factors on stability of railways in areas of permafrost distribution (example of Far East Road, Russia)

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Abstract. In 2019, the Institute of Permafrost of the Siberian Branch of the Russian Academy of Sciences and the Northwest Institute of Ecosystem Environment and Natural Resources of the Chinese Academy of Sciences concluded the agreements on joint research work. They decided to study the evolution of frozen soil at the base of roads and the territory adjacent to them, as well as to justify a set of measures to stabilize the permafrost situation. The works provide the study of the reaction of permafrost along the routes of railway lines in Russia and China. In Russia, the parties are examining in detail individual sections of the Far Eastern and Trans-Baikal railways. We present the results of surveys on one of these sections: a segment of the track dedicated to the Tynda station of the Far Eastern Railway. The object of research is very indicative from the point of the need to assess the dynamics of geocryological conditions in the strip of long-term operated linear structures. Here, the deformations of the roadbed have been manifested almost since the end of its construction (1974). Despite the implementation of several technical solutions in the form of cooling structures aimed at maintaining the soil temperature at the base of the structure in a frozen state, at present, the road is still subject to deformations. According to the current research results, it was revealed that the main reason for their occurrence is the flooding of the territory due to both natural and anthropogenic factors.

1 Introduction

Ensuring the stability of roads in the permafrost zone is one of the long-term tasks of permafrost engineering. Thousands of kilometers of railways and roads have been built within the area of distribution of frozen rocks, the largest in Russia of which are the Trans-Siberian, Baikal-Amur, Amur-Yakutsk highways, the Dead Road (Salekhard-Urengoy-Igarka), the Amur, Kolyma, and Vilyuy highways. Many of these objects, both built at the

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Beginning of the 20th century and relatively recently, are experiencing deformations associated with changes in the geocryological situation in their foundations and in the adjacent territories. The location of the cryolithozone in various climatic zones, geological structures, and natural zones determines a wide variety of conditions under which the interaction of the lithocryogenic basis of natural-territorial complexes and linear structures occurs. In this regard, the role of engineering-geocryological monitoring as a criterion for the reliability and trouble-free operation of geotechnical systems in the permafrost zone is significantly increased. Today the effectiveness and necessity of organizing such monitoring of roads in Eastern Siberia were proven\[1-14].

The expansion of the monitoring network on long-term highways and the organization of observation sites on new ones will allow:

- To replenish the base of factual material on the state and dynamics of changes in various conditions in the road lane, such a base is the basis for obtaining reliable predictive models;
- To work out new and adapt existing methods for studying the stability of roads in permafrost areas.

To determine the regional specifics of the behavior of road infrastructure facilities in the permafrost zone, from 2019 the Permafrost Institute, together with the Northwest Institute of Eco-Environment and Natural Resources of the Chinese Academy of Sciences and the Tynda Permafrost Station (a branch of Russian Railways OJSC), is organizing observation sites on the Far Eastern and Trans-Baikal Railways of Russia. Road sections for observations are characterized by continuous or island distribution of permafrost soils, long service life (tens of years), as well as deformations that were manifested in the first years after construction and continue to this day. We present the results of surveys on one of these sections: a segment of the track dedicated to the Tynda station of the Far Eastern Railway.

The research site is located 5 km from the center of the city of Tynda, between the Tynda and Shakhtaum stations of the Far Eastern Railway. According to the marking of the railway line, the section of the track between the marks of km 186 PK-5 and km 187 PK-5 is being investigated.
Fig. 1. The location of the Tynda monitoring site on a map fragment of the Far Eastern Railway (red rectangle) and layout of wells (1) and geophysical profiles (2) at the work site. Source: Compiled by the authors.

A federal highway and high-voltage power lines also pass within the boundaries of the work (see Fig. 1). The location of the site is beneficial from the point of view of monitoring the stability of various types of existing linear structures.
The Great Patriotic War, the construction of the Baikal-Amur Mainline (BAM) was curtailed (since 1997, BAM has been subordinate to the departments of the East Siberia Railway and the Far Eastern Railway), including the section of the road under consideration. Work resumed in May 1975, and in the summer of the same year, the construction of the subgrade was completed. The sediments of the embankment began to appear three to five years after its reconstruction. When developing a project for the reconstruction of the embankment, the designers of the Mosgiprotrans Institute (it specializes in various types of surveys and designing transport facilities) decided to eliminate the drainage slot located in a local depression at km 186 PK-7 + 05. However, this design regularly performed the functions of a culvert, due to which there were no stagnations of surface water directly at the subgrade on the upland side of the embankment before its reconstruction. The new ditch (provided for by the new project) is designed to collect and drain surface water. It worked properly only in the first years after it was cut. Five years later, this ditch turned into a chain of beaded lakes. Today numerous lakes, puddles of stagnant water (Fig. 2), local centers of subsidence, and sediment of the railway track are still noted at the base of the subgrade.

2 Materials and methods

To establish the factors that determine the duration of deformations on this section of the road, a set of works was carried out in the construction strip, which included:

- Aerial photography and thermal imaging by unmanned aerial vehicles;
- Geophysical research;
- Drilling of engineering-geological wells and thermometric observations in them;
- Laboratory determination of soil properties;
- Analysis of archival materials.

Geophysical surveys were aimed at delineating the development of dangerous permafrost processes at the base of the railway bed and the adjacent territory. The complex of geophysical studies included electrotomography [2, 13-17] and georadiolocation sounding [12].

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During field work, two experimental geophysical profiles were laid: the first (No. 1) along the railway track; the second (No. 2) across (Fig. 1). For aerial photography of the survey area, a complex with vertical take-off and landing "Geoscan 401" was used (Fig. 3). Well drilling was carried out by a self-propelled drilling rig dry and with compressed air blowing (Fig. 3) with a diameter of 132–76 mm. In the process of drilling wells, a field-wise description of all the varieties of soils encountered was carried out. Soil samples of the undisturbed structure were taken from the wells to determine the physical properties and thermophysical characteristics. The depth of the wells ranged from 5 to 20 m. The location of mine workings is shown in Fig. 1. The thermal conductivity of soils in the frozen and thawed state was determined using the ITP-MG4 "Grunt" instrument. At present, the thermal conductivity of most types of
soils is characterized in petrophysical reference books [1, 3, 4, 13, 16, 18]. However, with these definitions it was found that this parameter significantly depends on natural conditions, their evolution, and transformation in specific geodynamic and climatic processes that are characteristic of individual local areas. Publications of researchers involved in determining the thermophysical parameters of rocks have shown that thermal conductivity is determined by the degree of presence and opening of cracks, a saturation of rocks and cracks with moisture or ice, their lithification, etc. [5, 6, 7, 8]. Thus, the determination of the thermophysical properties of rocks should be carried out directly on each object (site) under study.

The temperature measurement in the wells was carried out both with portable thermocouples (the vertical spacing of the sensors is 0.5 m) and with autonomous sets with temperature measurement at a specified frequency (every four hours) throughout the year.

3 Results

The existing subgrade is a single-track embankment up to 6.0 m high. The railway traces the left-bank second terrace above the floodplain of the Tynda River with slightly undulating peat-moss marl, overgrown with a sparse larch forest.

Based on the results of well drilling and geophysical work, we found out that the soils at the base of the embankment are in a permafrost state. The lithological section of the base of the embankment is represented by lacustrine-marsh deposits (peat, peaty sandy loam, silty sand) up to 4.0 m thick, overlying alluvial deposits (sandy loam with pebbles, pebble soil with sandy aggregate) (Fig. 4).

The subsidence of soils that make up the upper part of the geological section during thawing is usually 40%–60% of the thickness of the thawing layer. Organo-mineral soils with subsidence of more than 70% are also found under peat deposits. Frozen lacustrine-marsh deposits are characterized by high ice content and the content of ice inclusions in the form of lenses and ice layers up to 0.5 m thick.
The thickness of the layer of seasonal thawing on the upper side of the embankment on the gentle slope of the southwestern exposure is 1.6–2.0 m, from the lower side on the moss-lead of 0.8–1.0 m. The temperature of frozen soils in undisturbed natural conditions varies in the range of minus 0.5–1.2 °C (Fig. 4).

According to the measurement data, the thermophysical characteristics of soils in the area under study vary within the following limits:

- Thermal conductivity in the thawed and frozen state varies from 0.53 to 1.72 W/(m·K) and from 1.28 to 3.12 W/(m·K), respectively;
- Volumetric heat capacity varies from 1,970 to 3,780 kJ/(m³·K) in the thawed state and from 1,810 to 2,200 kJ/(m³·K) in the frozen state;
- Thermal diffusivity varies from 0.14·10⁻⁶ to 0.87·10⁻⁶ m²/s in the thawed state and from 0.58·10⁻⁶ to 1.63·10⁻⁶ m²/s in the frozen state.

The most common cryogenic process at the monitoring site is ice formation. For example, at the base of the railway embankment and along the highway in the spring of 2020, the length of the icing reached a few hundred meters, with their width up to 20–30 m (Fig. 5). Landscape features indicate the ground type of aufeis-forming water.
of the survey, the icing did not pose a serious danger. However, the high dependence of their size on the amount of precipitation in the pre-winter season and the intensity of freezing of rocks make it possible to classify this process as potentially dangerous.

Fig. 5 Aufeis formation in the strip of roads and railways at the Tynda monitoring site (April 2020). 1 – thermokarst lake; 2 – icing. Source: Compiled by the authors.

In addition, the contact of aufeis-forming water with the upper structure of the embankment leads to intensive dispersion of macrofragmental soil that composes it [15].

Another type of potential aufeis hazard is the formation of aufeis mound. Thus, a few hundred meters from the investigated section of the railway in the direction of the town of Tynda, in a small valley of the stream, icing with a broken aufeis mound was recorded. The consequence of this rupture was the spread of blocks of ice up to 0.5 m or more in diameter at a distance of several tens of meters from the epicenter. The explosion of the mound occurred at a distance of 40–60 m from the highway.

Thus, the main cause of deformations of linear structures in the study area is the degradation of permafrost soils, the catalyst of which is the constant flooding of the territory with the formation of stagnant reservoirs at the base of the roadbed.

4 Discussion
To stabilize the settlement of the railway bed, through the joint efforts of specialists from the track services of the Baikal-Amur Mainline and the Tynda permafrost station, a project was developed and partially implemented. The project included the following measures:

- Construction of a drainage ditch on the upland side in poorly draining soil to prevent water infiltration into the body of the embankment;
- Backfilling of a rocky berm at the base of the upper (left along the course of kilometers) slope of the embankment 1 m high and 4 m wide to cool the underlying berm and the upper slope of the soil;
- Erection of a rock embankment with a thickness of 0.6–0.8 m on the lower (right along the course of kilometers) slope of the embankment;
- Installation of vapor-liquid self-cooling units with a diameter of 56 mm on a rocky berm along the embankment with a step of 2.0 m (Fig. 6).

![Diagram](https://example.com/diagram.png)

Fig. 6. Engineering-geological cross section along at 186 PQ 5+70 milestone.

1. crushed stone; 2. cobble soil with sand aggregate; 3. blocks with crushed stone and sand aggregate; 4. peat; 5. peaty sandy loam, sandy loam with cobbles; 6. cobble soil with sand aggregate.

Source: the archive of the Tynda permafrost station.

However, the proposed solutions did not have the expected effect. Subgrade settlements have become one-sided: the left edge of the embankment sags more than the right one. The depth of soil thawing under the left slope of the embankment increases with time, in contrast to the depth of thawing under the right slope, which practically does not change. The main reason for the different depths of thawing under the slopes is still the action of watercourses. Water filtration through the body of the embankment in the direction from the bottom of the ditch to the laying of the right slope and infiltration of atmospheric precipitation through the body of the embankment. A significant transverse slope of the earth's surface to the roadbed and the addition of the body of the embankment from draining soil became the conditions that determined the occurrence of filtration.

To stabilize the roadbed in the study area, a visible solution is the installation of additional drainage artificial structures. However, in this case, there is a problem of determining the route of surface water movement in the railway lane. Thus, under certain conditions, the movement of water occurs in dense vegetation with low intensity, practically without the formation of surfaces with open water. In addition, a significant part of water bodies is formed only during precipitation and floods. Apparently, for these reasons, when designing the route of the Baikal-Amur Mainline, in some places where the subgrade and watercourses intersect, artificial structures were not designed (no visible watercourse—no water gate) [9]. In this regard, the role of engineering-geocryological monitoring as a criterion for the reliability and trouble-free operation of geotechnical systems in the permafrost zone is significantly increased.
5 Conclusion

The work carried out on a single section of the Far Eastern Railway with a long service life showed the high information content of the use of unmanned aerial vehicles in assessing engineering and geological conditions in the strip of a linear structure. In particular, the boundaries of icing formation have been established on the study area. Based on thermometric observations in wells and geophysical studies, we established the depths of soil thawing at the base of the roadbed and determined the nature of its deformations. The results obtained demonstrate the need to organize engineering-geocryological monitoring at linear structures in areas of permafrost distribution.

References

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