

Analysis of roadbed destabilization causes on sections with thaw underground ice and reinforcement reconstruction measures

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Abstract. The roadbed on over-wet permafrost and underground ice sections requires a thorough examination after a long-term exploitation period. Its strengthening design requires an individual technological approach. The paper considers two examples. The first one is located on the 28th km section of the Chulman passing siding entrance, and the second one is on the 59th km of the Amur-Yakutsk Mainline. The causes of the roadbed deformation are determined by the analysis of different surveys, special engineering and geological methods as well as the geometry car ongoing data. Some new technological design solutions that are patented and introduced on working sites are covered in the paper.

1 Introduction

Approximately 80 % of the territory of the Russian Far East is located in the zone of permafrost. FESTU has been dealing with issues of construction, reinforcement and maintenance of the subgrades and other structures built on permafrost since the 1960's and has dealt with the structures of the Baikal-Amur Mainline (BAM) since the beginning of its construction. The problem of preserving the stability of the railway subgrades in the North of the Russian Far East under the conditions of long-term operation on high-grade permafrost soils remains relevant in the process of their further operation. The BAM was put into operation more than thirty years ago, and the Amur-Yakut Mainline - more than 20 years ago. As an example, settlings only on the thawing permafrost soils along the major direction of the Northern Latitudinal Railway Khani-Tynda-Komsomolsk-Sovetskaya Gavan' make up 51.9% of the whole stretch of the settling areas of the Far Eastern railway and the subgrade undergoes deformation along the distance of 1,484 kilometers (62%) of the subgrade extent. Two thirds of the whole length of subgrades were constructed in accordance with the individual projects.

2 Subgrade problems on certain dangerously deforming sections

The permafrost-soil conditions in the foundations of the subgrades, landscape and surface microrelief of the adjoining territory have changed as a result of the malfunction of drainage

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facilities, underflooding and water influx into the territory. In addition, soils that lose strength due to the increase in train loading, natural disasters and calamities undergo destructurization and deformation. Deformations take the form of plastic deformations, heaving of clay soils, and splashes from ballast hollows, etc. The problems of the railroads of Far Eastern North are connected with the destruction of the subgrade stability caused by the loss of bearing capacity of the soils of the subgrades. Thus, the problems do not decrease but evolve into different types of problems. On the average, 1/3 of the subgrade on the BAM is subject to deformation; firstly – to deformation caused by “heat” (“thermal”) settling due to permafrost deformation, then – to cryogenic deformations in the form of ice heaving, aufeis, pressure-tight mechanical piping and others.

Norms and regulations for maintenance of the subgrades and artificial structures are obsolete and those for the conditions of the Southern permafrost zone do not meet the requirements of the real conditions in many respects and need correction.

All kinds of anti-deformation and preventive measures are aimed at the achievement of higher strength parameters of soils of subgrades and its foundation within the minimal time limit and ensuring their long-term efficiency.

2.1 Reasons for the loss of the subgrade stability on the road sections with permafrost soils

Firstly, long term operation of the roads on permafrost soils is accompanied with certain specific features connected with the temporal staging of natural stabilization of the temperature-humidity conditions in the course of operation. Secondly, long term operation depends on the consequences of thawing underground ice and the specific features of consolidation of icy permafrost soils.

After 15-20 years of operation, soils of the 3rd and 4th categories of thermal soil subsidence form a talik zone in the foundation of the road embankment. In the Transbaikalia and the BAM regions (with the heights of foundations of 1.5-4 meter), the top bound of the talik zone forms at the depth of 3.5-5.5 meters from the open surface. As the long-term investigation of the research laboratory “Bases and Foundations” has shown, “talik” is a kind of “healing”, transitive (absorbing or aligning the temperature condition) layer between permafrost and the engineering structure. During the first 18-20 years of operation, intensive subgrade settlements of up to 200 mm per year and more that take place then the settlements become less intensive, up to 40-50 mm/year which lasts for decades.

After a relative stabilization of subsidence caused by permafrost degradation and thawing of ice interlayer (initial displacement), the long-term displacement connected with the rheological processes begins; and the quality of deformation changes. The intensity of these processes increases with the increase in the vibration-dynamics loads from train (mass of the train and axial loads) and with the work of continuously working leveling machines or track renewal train. At present, in 70% of the cases under survey the depth of thawing through is 7-12 m. However, permafrost on the left and on the right of the subgrade still continues to exist as it had been before. The most vulnerable zones of the subgrade are in the near-bottom area. In the regions of permafrost and deep seasonal frost penetration, freeze-and-thaw ground processes and soil deformation are seriously influenced by suprapermafrost underground waters. Characteristic deformations of subgrades, connected with the transition of suprapermafrost (underground) waters into pressure mode during the winter period are as follows: blowup and subsiding deformations, frazils, formation of icing mounds (hydrolaccolytes), aufeis mechanical piping, plastic deformations and soil blowup.

FESTU conducted patent research in order to analyze the latest progressive methods and technological solutions aimed at the stabilization of the earthen subgrades.

2.2 Results of the patent research conducted by FESTU

According to the conducted patent research the following overseas companies show active inventive work: Tso sa, fr aea technology plc, gb; Jr higashi nippon consultants; Jr kyushu consultants kk; Mitsubishi heavy ind ltd; Tokai ryokaku tetsudo kk; Nippon electric co; Nec san ei instruments, Jr и др.

During recent years China has been actively involved in research of the problem of reinforcement of subgrade and foundations of artificial structures under the conditions of high-grade permafrost. China's active work in this field is determined by putting into operation the Qinghai-Tibet railway mainline. This is confirmed by a significant number of patents issued for inventions and utility models as well as publications on this problem. The following institutions can be distinguished: Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou; Central South University, Changsha. The majority of these works are devoted to measures for the roadbed stabilization on local sections. These works are of innovative character and practical importance but unfortunately they are not applicable for extended (up to several kilometers long) deforming sections of roads, especially on marshland sections. The approach to the choice of measures should be alternative. The major consideration for the choice of project is the staging of stabilization of the subgrade.

3 Approach to the choice of anti-deformation measures with consideration to the staging of restoration of thermodynamic equilibrium with the system "earth roadbed – permafrost soils of foundations"

During the first period of approximately 10 years, restoration of the permafrost condition with the help of chiller systems possibly makes sense if this first principle is also followed in the process of operation; during the following 5-7 years with additional chiller systems; but in future alternative solutions must be developed. In the first case, the solution for preservation of permafrost condition is reasonable; in the second case restoration and reinforcement is reasonable for the sections with underground ice only. Fig.1 shows the graph of temperatures while forming the "talik" zone during the period from 1988 to 1993 (the year of construction is 1976).

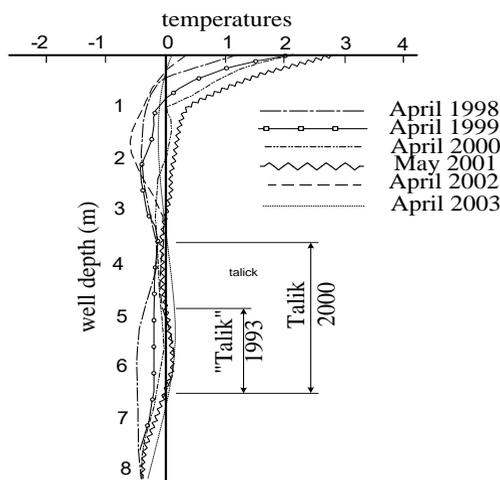


Fig. 1. Temperature curve graph for the well in the foundation of the earthen roadbed.

At present in 70 % of cases the permafrost lowered itself to the depth of active zone 7-12 m. Nevertheless, on the left and on the right, permafrost still exists in the same condition.

Thermo-dynamic equilibrium that forms in the earthen technical structure 20-25 years after filling of the roadbed, determines the optimal terms for track upgrade (second track, double track inserts) avoiding harmful impact on the subgrade of the first track. Simultaneously, the subgrade of the second track needs reinforcement with various reinforcement devices.

In the regions with long-term permafrost and deep seasonal freezing, the impact of suprapermafrost (subsoil) waters needs to be eliminated as they possess pressure and often cause the deformations of earthen roadbed, its foundations and adjoining sections of the soil surface: blowup and subsiding deformations, augeis, formation of icing mound (hydrolaccolytes), icing mechanical piping, plastic deformations and soil blowup. Especially unpredictable consequences are of the deformations of earthen roadbed on the sections where ground ice melts out and with high iciness of permafrost soils.

The FESTU research laboratory “Bases and foundations” has developed various measures for elimination of deformations on the sections with different types of deformations. Many of the developed measures were introduced and tested on many sections.

Sections 4 and 5 below, describe the cases of earthen roadbed deformations on sections with melting ground ice and the specific features of consolidation of icy permafrost soils.

3.1 Deformation of track with thaw of underground ice on KM 28 PK 3 - PK 10

According to the contract between FESTU and OJSC “Yakutia Railways” in 2015-2016, several sections of earthen roadbed were examined on the section Neryungri St. - Tamarak siding/passing track of the Berkakit – Tommot – Yakutsk rail line. This examination was aimed at the development of projects for anti-deformation measures.

One of such sections is the section of roadbed in the front entrance of the Chul’man station of Denisovskiy-Chul’man stage (PK6 – PK10 KM 28), located on the right bank of the Chul’man river, 28 km north-west from the town of Neryungri (Fig. 2).



Fig. 2. Distortion of plan and profile on the section with thawed underground ice.

The region is characterized by island distribution of permafrost soils. The average depth of seasonal frost penetration is 4.0 m on watershed and 1.5 m in the valleys of rivers and brooks. Soil temperature at the depth of 0.8 m fluctuates from -0.4°C to -9.5°C in winter; and from $+2.1^{\circ}\text{C}$ to $+11.8^{\circ}\text{C}$ in summer. The landscape in the section is mountainous and hilly. Ground elevation marks along the axis of the road do not exceed 680 m. Road-building

climatic zone is 1A with force-eight seismicity. Climate is extremely continental. Within the boundaries of the area under study, soil frost heave and high seismic activity of the region should be mentioned among the present day endogenous geological process that negatively influence the construction.

The section under study is a one track unelectrified section of railway. Rails laid in the section are 25meters long of R-65 type. Sleepers are wooden.

Ballast is of the crushed quarry type. The engineering-geological survey conducted by FESTU showed that the width of the ballast layer under sleepers is from 25 to 60 cm.

On location earthen roadbed in the section PK6 – PK10 KM 28 showed dangerous deformations of the roadbed in the form of settlements and heaving. The earthen roadbed in the section under reconstruction is an embankment of rocky and crushed stone ground, and pebble and gravel soils with rock terraces. Displacements are caused by thawing of up to 2 meter thick ice layers in the foundation of the embankment. The embankment loses stability because of underground flooding of the thawed cavities in the foundation filled with fine-grained drain soil. The deformations are connected with the blowup of water-bearing soils in winter period; with aufeis mechanical piping during the pre-winter period caused by the pressure filtration of underground and surface waters from hillside and corrosion of fine-grained soils from cavities to low side of the roadbed; and with plastic extrusion of loose soils during summer.

Engineering geological works established 3 layers in the deforming section of the roadbed: layer-1 – filled-up clod or boulder soil (t QIV); layer-2 – fine, mellow, water saturated, icy sand (a QIII-IV); layer-3 – pebble stone soil of middle degree water saturation (a QIII-IV) (according to GOST 25100-2011 and GOST 20522-2012).

For the period of the survey (September) soils of the layer of seasonal thawing-freezing were in thawed condition down to the depth of 5.4-9.0 m with a middle degree water-saturation. In the wells, permafrost was found from the depth of 5.5 m; in some wells no permafrost was found. The depth of seasonal thawing-freezing depends on multiple factors (summer air temperature, vegetation and mossy cover, humidity and lithological composition of soils in the aeration zone, etc.)

All distinguished potentially dangerous sections are characterized by approximately the same degree of hazard level – correlation-refraction method showed that all anomalous intervals display deepening of the upper boundary of hard rock; electro-tomography and georadiolocation detected thickening of water-bearing loose ground.

Geophysics works within the interval PK 273 – PK 280 also distinguished intervals of potentially dangerous exogenous processes.

Electrical survey and seismic prospecting did not establish unambiguously interpreted intervals of distribution of frozen rock. Within the borders of the section under survey, water bearing soils of the upper layer of the open-cast are present practically everywhere.

According to the data of the geometry car the major reason for deformations is the underground flooding of the soils of the subgrade and of the body of the earthen roadbed in the cutting caused by the inflow of ground and surface water from the slope made up of crumbling, rocky soils and the malfunction of the surface ditch on the right and the water-diversion ditch on the left. As a result, on MP 278+50 the weathered floury soil of the roadbed is overwettted which causes fundamnental blowup above the ladder track in winter and piping of soil particles due to pressure filtration on PK 275+85.0, the former (before construction) location of the flow off. Due to the malfunction of the side drain, surface water flows down the slope into a natural ravine at the bottom of the subgrade and undermines it on KM 28 PK5+85.0, which results in subsidence on PK 6, and skew shifts on PK 8 – PK 9.

Thus, multiple research methods and land investigation gave reliable reasons for the distortion of the plan and profile of the track in the entrance to the Chul'man station that

endanger safety and discontinuous traffic on the section with thawed underground ice in the foundation of earthen roadbed.

3.2 Choice and designation of measures for roadbed reinforcement on KM 28

The project envisages the realization of a complex of anti-deformation measures as follows:

- erection of an integrated filter embankment – PK 5+85;
- erection of cold-proof insulated drainage of a closed type on the right (PK 6+00 – PK 8+50) and on the left (PK 6+00 – PK 10+00);
- laying out of two-level drainages;
- restoration of the profile of intercepting drain on the right that included filling holes and leveling the territory near the roadbed with nondrainable soil;
- erection of cascade/stepped drop in the mouth of the intercepting drain and drainage on the right of PK 6+00 to PK 5+85.

3.3 Deformation of roadbed on the section with underground ice on KM 58 PK1 – KM59 PK 3

From the geo-cryologic prospective the section is located in the zone of island distribution of permafrost soils. For the period of the survey (October) the soils of seasonal freeze-thaw cycle were melted down to the depth of 4.0 m, clay soil was plastic. The depth of the seasonal freeze-thaw depends on many factors (summer air temperature, vegetation and moss layer, humidity, and lithologic composition of soils in the aeration zone, etc.). The deformations are similar to the previous case – of blowup-slump character.

On-stage geo-physical field investigations were conducted in summer period: ground penetrating by a geo-radar OKO-2 equipped with the antenna units “Triton” and seismic prospecting by a correlation refraction system TELLS-3. Electric sounding was performed in accordance with the preliminary developed network of geophysical profiles.

When surveying section PK 58+1.00 – PK 59+5.00, longitudinal profile 0 was investigated within the interval PK 58+1.00 – PK 59+3.00. The survey established that insecure rock soils of discharge zone along the profile are intermingled with the high strength solid rock, laying close (approximately 1.5 – 2.0 m) to the open surface (PK 57+5,4 – PK 57+7.2; PK 57+8,0 – PK 57+8.4; PK 58+0.0 – PK 58+1.2).

According to the data of the geometry car passages, major deformations on 58 KM take place as follows: in July-August - subsidence on PK 1,2, and skew shifts and subsidence on PK 8; in November - blowup on PK 1-3, PK 10. On 59 KM deformations in the form of slump take place on PK 1- 2, and PK 7 – PK 9. Electric tomography showed that the major specific feature of the section under survey is practically discontinuous watering of the upper part of the cutting.

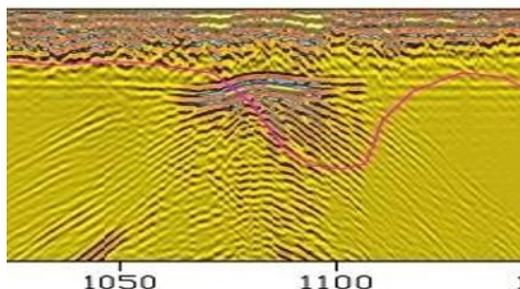


Fig. 3. Anomaly of intensive re-reflections in the zone of the massif soil loosening.

Data of seismic prospecting by the wave correlation-refraction method allow us to assume presence of intervals of significant deepening of the hard rock upper boundary in the places with thawed underground ice.

All distinguished potentially dangerous sections are characterized by approximately the same degree of hazard – all anomalous intervals display deepening of the hard rock upper boundary (according to correlation refraction data) and thickening of loose water-bearing deposits (according to the data obtained from electric tomography and ground penetrating radar).

Thus, deformation on KM 58-59 are similar to the deformations on KM 28. They are of blowup-slump character caused by different reasons but united by such parameters as deepening of the hard rock upper boundary and thickening of loose water-bearing ground deposits.

4 Conclusion

The earthen roadbed on permafrost soils under conditions of long-term operation is subject to deformations: firstly, to “heat” settling due to permafrost degradation; then – to “cryogenic” due to ice heaving, icing moulds, pressure mechanical piping and others. Especially unpredictable deformations are the deformations of subgrade in the sections with thawed underground ice and long-term permafrost soils with high ice content. Regulations for the maintenance of subgrades and artificial structures are out of date and do not reflect the real situation in the southern zone of permafrost and, consequently, need correction.

In the first place, the impact from the supra-permafrost (ground) waters with pressure force flow should be eliminated. All kinds of anti-deformation and preventive measures are aimed at high strength properties of roadbed and foundation soils in the minimal time and ensuring their long-term performance. At present FESTU has certified and patented technological solutions for the reinforcement of the existing subgrades, as well as new designs for drainage and drainage facilities intended for elimination of pressure underground waters and water circulation facilities. Thermo-dynamic equilibrium that forms in the earthen structure 20-25 years after filling of the roadbed determines the optimal terms for track upgrade (second track, double track inserts) avoiding harmful impact on the roadbed of the first track. Simultaneously, the roadbed of the second track needs reinforcement with various reinforcement devices. In our opinion, in search for constructive-technological solutions under the conditions of permafrost alternatives must be found.

For particularly dangerous sections “Industry standard for technologies of reinforcement of dangerously deforming sections of earthen roadbed under severe natural-climatic conditions” are necessary for adoption of operative solutions for stabilization of earthen roadbed that would ensure a necessary risk level on the sections with deformations of abrupt and poorly predictable character.

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