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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

DEFORMATION AND STABILIZATION OF MOTOR AND RAIL ROADS WITHIN THE NORILSK–TALNAKH TRANSPORTATION CORRIDOR

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Key factors that cause deformation of motor roads and rail roads of the transportation corridor between the cities of Norilsk and Talnakh have been revealed from data of field monitoring, thermophysical modeling, satellite imagery, and archive survey reports. There are four main types of deformation in the area, all associated with bearing capacity loss in permafrost soils under the roads. Deformation of roads results from natural and engineering causes: flooding and thermokarst of low permeable ice-rich soils and few and poorly operated drainage systems, respectively. Each type of deformation requires specific geotechnical measures for monitoring and stabilization of roads.

Permafrost, roadbed, deformation, embankment, settlement, thermokarst

INTRODUCTION

Deformation of motor roads and railroads on frozen ground poses serious problems to development of northern regions with complex permafrost settings. Field observations in areas of the Baikal-Amur and Trans-Siberian railways, as well as in Tibet and Altai, show rapid deterioration of subgrade and native soils, progressively increasing erosion, and loss of stability and safety of roads [*Minkin and Chizhov, 1989; Peretruhin and Potatueva, 1989; Rozenberg, 1989; Shesternev and Chashchina, 1989; Ospennikov, 2000; Kondratiev, 2011, 2012; Isakov et al., 2013*]. The greatest deformation of rail tracks was observed in the so-called "dead road" (sites 501 and 503) from Salekhard to Ermakovo-Igarka, with construction and operation of its some segments stopped in 1953 [*Pashkova, 2007*]. Geotechnical monitoring in 2007 likewise revealed risks to safety and stability of operation along the Ob'–Bovanenkovo railway in the Yamal Peninsula [*Tsvetkova, 2008; Panchenko, 2009*]. Investigation into deformation of roads is especially important for the Norilsk industrial district which is located in complex natural conditions and has a long history of development, including construction of roads.

Norilsk is among the largest industrial centers in the zone of permafrost. Traffic is especially heavy on roads that connect Norilsk with other populated places like Talnakh and Dudinka. Cryogenic deformation of roadbeds and embankments in the area reduces the traffic capacity and creates hazard to safety of automobile and railway transportation.

STUDY AREA

The Norilsk industrial district is located in a zone of complex engineering-geocryological conditions and a harsh climate, with a mean annual air temperature of –9.4 °C and frequent snow storms and snow drift in winter [*Velli et al., 1977*]. Roads and other linear structures are built on ice-rich ($I = 0.3–0.6$) fine-grained lacustrine-fluvial clay and clay silt of the Valek terrace [*Demidyuk, 1989b*] that encloses ground and wedge ice. Ice-rich deposits may be as thick as tens of meters. Ground temperatures in natural conditions at the depth of zero annual amplitudes vary from 0 °C (at the boundary of taliks, including near the banks of the Norilskaya River) to –3...–5 °C [*Demidyuk, 1989a*]. The permafrost temperature in the surroundings of the road network (e.g., Ol-Gul resort near Valek Village) is commonly no colder than –2 °C [*Grebenets and Ukhova, 2008*]. Unfrozen soils occupy about 30 % of the district area [*Sheveleva and Khomichevskaya, 1967*] and are mainly taliks under the Norilskaya River and under large thaw or permanent lakes; note that some roads follow the very borders of lakes. High thermoskarst activity on the Valek terrace has produced thaw lakes alternated with remnant cryoplanation surfaces that survived thermal erosion. Field monitoring along roadways and railways revealed numerous small lakes that result from ponding of ephemeral streams crossed by embankments, as well as active groundwater seepage. The depths of most lakes measured in August–September exceeded 0.75 m, which is the critical depth indicating rapid thermokarst formation in the area [*Demidyuk and Lebedeva, 1977*].

CONSTRUCTION HISTORY AND SOME ENGINEERING FEATURES OF MOTOR AND RAIL ROADS IN THE NORILSK REGION

The transportation system in the Norislk area developed simultaneously with its industrial development. First, a railway and an unpaved earth road from the Valek pier to Norilsk and the Dudinka–Norilsk railway were built in the middle and late 1930s, respectively. The rail and motor roads were extended to Talnakh in the 1960s, when a new city was being constructed to develop the Talnakh ore field. In 1963 a combined automobile and railway bridge crossing of the Norilskaya River was set into operation, and a pulp pipeline was laid over the bridge structures in the late 1970s. The pipeline produced additional 40 t load on the crossing foundation. Note that the bridge left support experienced considerable deformation during the period between the operation onset and the 1980s when thermosyphons were installed to freeze it into the riverside [*Grebenets et al., 1999a*]. The previously existing road segments were reconstructed: the rail track was straightened and the roadway was paved with asphalt.

The embankments of both rail and motor roads in the Norilsk–Talnakh transportation corridor vary in height from 1.0–1.2 m to 18–20 m and are much lower (4–6 m on average) under the automobile road. The embankments consist of debris with 30–40 % of filling material (land waste, sand, silt or smelter slag with fine soil). This material is impermeable for water and does not allow convection of cold air inside. Large embankment widths, locally reaching 60–80 m, are responsible for the formation of broad flooded zones near the slopes. There are no thermal boreholes accessible for inspection along the road slopes.

Safety of roads in the Noilsk area is an urgent issue [*Grebenets et al., 1999a,b*]. The knowledge of deformation causes is indispensable for reasonable stabilization measures to ensure long-term safe operation of roads, while discrimination between morphological and genetic deformations will improve the stabilization efficiency.

METHODS

In August–September of 2010 and July 2011, 15 km of railways and 19 km of motor roads were investigated between Norilsk and Talnakh. The studies included field monitoring, deciphering of remote sensing (space borne) data, and analysis of archive survey reports provided by the Agency for Road Maintenance and Snow Defense of Norilsk city. Field monitoring focused on types and extent of roadbed deformation; extent of cryogenic and other erosion of embankments and the surrounding areas; and stability of structures. Satellite images were used to contour zones of flooding and cryogenic hazard. Analysis of archive reports revealed dynamics and recurrence of deformation within different road segments.

The temperature field under the roads was simulated using the WARM software [*Emeliyanov et al., 1994*] because there was no measured ground temperature data available. Climate and other data required for modeling were pre-processed and processed using a method suggested by *Khrustalev* [*1999*]. See Table 1 for mean monthly temperatures of fill and native soils used in the calculations. In winter months, the temperature of slopes and adjacent areas was assumed to be equal to that of snow.

Albedo was assumed to be 0.1 for the embankment top (asphalt-concrete pavement and ballast strongly contaminated with petroleum products) and 0.14 for the slopes (debris). Snow thickness was included assuming that snow was regularly removed from the carriage way and distributed evenly over the slopes:

$$H_{\mathrm{sl}} = H_0\left(1 + S_{\mathrm{top}}/2S_{\mathrm{sl}}\right), \qquad (1)$$

where H_{sl} is the snow thickness on slopes, m; S_{top} is the cross-section length of the embankment top (carriage way), m; S_{sl} is the cross-section length of slope, m; H_0 is the natural snow thickness, m.

The effect of snow drift on snow thickness was neglected in the modeling. Mean monthly snow density was assumed according to the table of *Kudryavtsev et al.* [*1979*] because no data was available on the snow density on slopes and nearby areas. Winter snow density was assumed to be the maximum in spring, when the compacted snow becomes thinner.

Table 1. **Mean monthly temperature of natural ground and fill**

Year*	Month	Ground surface temperature*, °C	Month	Ground surface temperature*, °C
−9.4; −7.9; −7.5	1	−26.9	7*	14.3; 19.0; 20.4
	2	−27.2	8*	11.4; 15.5; 16.9
	3	−21.9	9*	4.0; 7.7; 9.1
	4	−13.9	10	−9.5
	5	−4.8	11	−20.2
	6*	7.0; 12.1; 13.4	12	−25.1

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* Temperature of natural ground surface/temperature of slope surface, without regard to direction/temperature of embankment top.

Table 2. **Principal properties of soils, according to *Construction Rules* [*1990*] and *Khrustalev* [*1999*]**

Soil	P, kg/m^3	I, u.f.	Λ_{th}, W/(m^2·K)	Λ_f, W/(m^2·K)	C_{th}, J/(kg·K)	C_f, J/(kg·K)	Z_v, J/kg
Ballast (fill pad)	1900	0.05	1.45	1.51	$2.36 \cdot 10^6$	$2.19 \cdot 10^6$	$3.18 \cdot 10^7$
Gravel-debris mixture (fill pad)	2060	0.03	2.09	2.15	$2.62 \cdot 10^6$	$2.43 \cdot 10^6$	$2.07 \cdot 10^7$
Sand (fill pad)	1800	0.20	2.68	2.85	$3.16 \cdot 10^6$	$2.41 \cdot 10^6$	$1.21 \cdot 10^8$
Silt (fill pad)	1800	0.20	1.86	1.98	$3.16 \cdot 10^6$	$2.41 \cdot 10^6$	$1.01 \cdot 10^8$
Clay silt (native soil)	1200	0.40	1.57	1.80	$3.10 \cdot 10^6$	$2.11 \cdot 10^6$	$1.08 \cdot 10^8$

Note. P = soil density; I = ice content; Λ_{th}, Λ_f = thermal conductivity of unfrozen (thaw)/frozen soil; C_{th}, C_f = heat capacity of unfrozen (thaw)/frozen soil; Z_v = heat of soil thawing (freezing).

The temperature field was modeled for embankments of different heights (2, 6 and 10 m), with their base widths 15, 27 and 39 m, respectively, a 9 m wide top, and 1:1.5 slopes. The embankment material was assumed to be a mixture of gravel, debris, fine sand, and silt, with crushed stone ballast in the upper 1 m in all cases. Native soils beneath the subgrade were ice-rich clay silt similar to that stripped in test pits at the subgrade base in the course of field monitoring. The density, ice content and thermal properties of soils used in modeling were as listed in Table 2. The initial natural ground temperature was assumed to be −1.5 °C all along the model depth, while the fill temperature was varied downward from −4 to −2 °C, at equal steps, with the stepsize depending on the embankment height.

The temperature field dynamics was modeled for 50 years, which corresponded to the lifetime of the railroads and motor roads from their construction in the 1960s to the present.

RESULTS AND DISCUSSION

Field monitoring reveals deformation of motor and rail roads over at least a half of their length. It may be of larger or smaller extent and appear in diverse forms: soil subsidence; cracks in asphalt pavement of carriage way and shoulders; bending of rail tracks; erosion (detachment and slumping) of slopes. Unstable segments occur at every 3 km on average and pose risks to traffic safety. They are frequently associated with terrain changes, embankment flooding by thaw lakes and dammed drain ditches, while erosion of slopes along motor roads often produces transverse cracks.

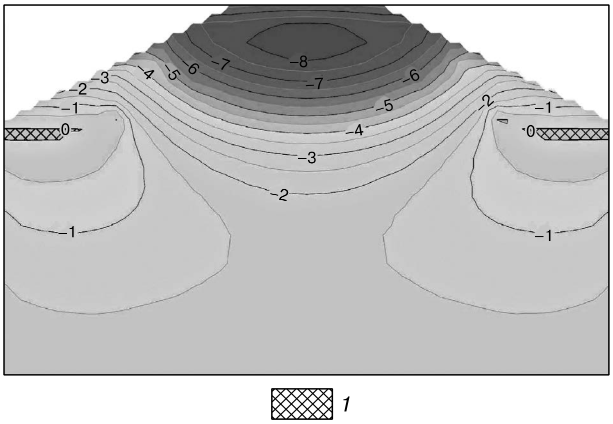

Fig. 1. Temperature pattern under a 6 m high embankment in the end of cooling season, 50th year of operation.

Numerals show ground temperature in °C; 1 – soil above 0 °C.

An important role in deformation belongs to poor drainage of embankments with less than one culvert pipe per 1 km of road, which is insufficient to mitigate flooding by ephemeral streams. More than 75 % of pipes have flaws (wrong angle, lack of discharge, displacement of concrete segments, leakage through walls) that interfere with their normal operation.

According to the monitoring results compared with reports of previous surveys (2007), the number and surface area of deformed segments increased in spite of repairs undertaken in 2008. In 2010 and 2011, asphalt pavement was deformed within the same segments as in 2007, but smaller deformations (less than 5 m^2) did not show such continuity. Thus, large deformations must result from some geotechnical trends in the foundations rather than from pitfalls of remedial works.

The modeled temperature pattern of embankment and natural ground shows that permafrost under the 6 m high gravel + debris embankment generally does not thaw after 50 years of operation, except for small taliks at the slope toes (Fig. 1). In the case of a wetter sand-silt embankment material, larger amounts of soil become unfrozen and taliks appear under slopes, with a thaw depth of 1–2 m.

Both natural and fill materials in 2 m high embankments freeze up completely in winter and thaw in summer, while natural ground beneath the subgrade thaws to 1 m. Natural ground under 10 m embankments thaws as deep as 4 m if they are built of wet sand and silt but remains frozen if they are made of gravel and pebble, because the warming effect of snow is weak.

Joint field monitoring and modeling results allowed classifying deformation according to morphology and hazardous surface processes. This classification has implications for the origin of deformation and respective engineering solutions to protect the road parts exposed to deformation of different types. Main types of deformation in motor and rail roads in the Norilsk industrial district are discussed below.

1. Settlement of high embankments in the longitudinal direction is somewhat similar to regular dip changes that follow the terrain but this specific type of deformation differs in irregularity and great number of dip changes along and across the road and in sharp breaks of the longitudinal profile. The settlement is especially prominent where the embankment crosses different landforms (Fig. 2). Embankments in thus deformed zones bear traces of forced remediation: filling, replacement of sleepers and rails in railways or patches in motor roads, including over transverse asphalt cracks. The deformation arises in high embankments upon permafrost in places where the depth to permafrost changes within thaw lakes and remnant cryoplanation surfaces.

Warming at the subgrade base, which affects soil strength [*Construction norms..., 1990*] and thaw depth, is known [*Lisitsyna et al., 1989*] to correlate with the cross-section height of embankments. This correlation is valid for the study area, as confirmed by our modeling: in the end of the warm season in the 50th year of operation, the permafrost temperature was from −1.6 to −2.4 °C at a depth of 4.5 m below 2 m high embankments of gravel and pebble, from −1.2 to −1.9 °C under 6 m high embankments, and −0.8 to −1.5 °C under embankments as high as 10 m. Ground temperature decreased regularly toward the road axis in embankments of all heights. The magnitude of relative warming under high embankments is equivalent to hundreds of KPa loss in soil bearing capacity [*Construction norms..., 1990*]. On the other hand, higher embankments cause greater loads on natural ground and induce creep [*Vyalov, 1978*]. The “scissors” between higher mechanic loading and bearing capacity loss in soils are mainly responsible for settlement along high embankments. Thermokarst depressions at the slope toes of embankments accommodate snow in winter and water in summer, whereby erosion progresses and thawing soils become wetter.

Settlement of this kind is especially widespread in the study area, its amount varying from a few tens of centimeter to a few meters within segments from 25–50 m to a few hundreds of meters long. Settlement of high embankments is not very hazardous as it does not produce sharp height contrasts to pose traffic safety risks. However, it causes wear to rails in railroads and destroys asphalt on motor roads, which reduces traffic speeds and increases fuel consumption.

Cooling with thermosyphons is the most efficient way to mitigate the warming effect of embankments, as well as snow and water pools. Other ways implying control of heat exchange across surfaces require either much labor (snow removal along the road and preventing snow accumulation in depressions) or engineering efforts (drainage). Thermosyphons have been used successfully in the area for providing stability of civil objects and some water works. For instance, deformation is insignificant in thus stabilized motor and rail roads that pass the dam on Lake Dolgoye.

2. Local embankment settlement can reach several meters long, 10–20 cm deep, and span the whole carriage way surface. It arises mainly in places where the embankment crosses perennial or ephemeral streams and drain ditches (Fig. 3). If drainage structures are few or malfunctioning, streams can produce local pools at slopes and drained water can pass through the embankment body or through thawed soil under it. Persistent local zones of drainage and flooding at thalweg crossings cause thawing and subsidence of subgrade and the underlying soil. Field monitoring shows that lakes within local settlement

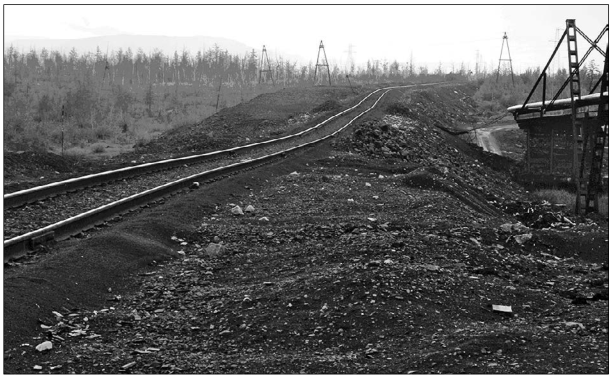

Fig. 2. Settlement along a high railway embankment near Valek crossing loop.

Wavelength about 120 m, August 2010.

Fig. 3. Local carriage way settlement within a segment of a broken drainage pipe.

Norilsk–Talnakh roadway, 16th kilometer, September 2010.

zones exceed the critical depth of ~0.75 m (see above), which creates prerequisites for thawing of natural ground under roads.

The zones of local settlement along the Norilsk–Talnakh roadway have complex geometry that apparently follows the geometry of drainage channels beneath the embankment. Such deformation, more common to 10 m high embankments, poses greater risks to traffic safety than the longitudinal settlement of high embankments because it causes contrasting changes within short segments of the roadbed profile and deforms heavily the roads themselves.

Mitigation of local settlement implies installation of additional drainage structures during road reconstruction, as well as drainage of the adjacent areas.

3. Deformation of low embankments (from 0.7 to 3.0 m), with relatively small displacement, may occur both along and across railways as, for instance, in the segment between Golikovo station and Valek crossing loop. The stability of uppermost natural ground under low embankments with relatively small cross-section areas depends more strongly on dynamic loads from trains than in the case of higher embankments. These dynamics loads are especially high within a few meters below the surface and decrease exponentially by scattering over the embankment body [*Shakhunyants, 1987*]. Relatively large dynamic loads transferred to natural ground under railways lead to significant elastic deformation of permafrost in winter [*Tsytovich, 1973*] and to liquefaction and thixotropy of soils in summer when permafrost thaws, which interferes with the transportation safety and efficiency.

According to the calculated temperature patterns under low embankments, both subgrade and natural soils thaw to a depth of 1 m by the end of the warm season in spite of strong cooling during winter. The impact of dynamic loads on the 1 m wet unfrozen layer, as well as the wave-like load propagation, are responsible for high intensity of deformation though at minor displacement.

Trains have to slow down, sometimes to 10 km/hr, at such deformed sites. The related stresses cause failure of rails and sleepers which have to be replaced very often.

The mitigation measures include reinforcement of both permafrost and seasonally thawing subgrade and natural soils in order to increase their strength and provide more uniform distribution of loads. Some additional stabilization effect can come from thermosyphons.

4. Deformation of slopes within the studied segments of motor and rail roads has diverse forms: erosion, cracks along shoulders, detachment and slumping in both slopes and carriage ways. The deformation mainly arises as natural and fill soils at the slope base lose bearing capacity, which leads to settlement, slope steepening, and weakening of soil freeze-up in the embankment body. The temperature field modeling shows that taliks appear beneath slopes almost in all cases, except for low embankments (Fig. 1). In the case of embankments composed of wet soil, taliks form in both fill and native soils which makes them more vulnerable to erosion upon spring snow melting. Cracks at the road edges (tops of slopes) result from stresses in fill caused by thawing-related subsidence of native soil under the subgrade, as well as from seasonal thawing of embankments during low-snow winters in the area. Note that the front of seasonal freezing of embankment in this case is directed mostly off the road axis, while the slopes covered with thick snow freeze up very slowly. As a result, quite large temperature gradients (to 20–25 °C/m) arise in the beginning of freezing, which may induce frost cracking in subgrade soils. The direction of freezing off the carriage way in the case of

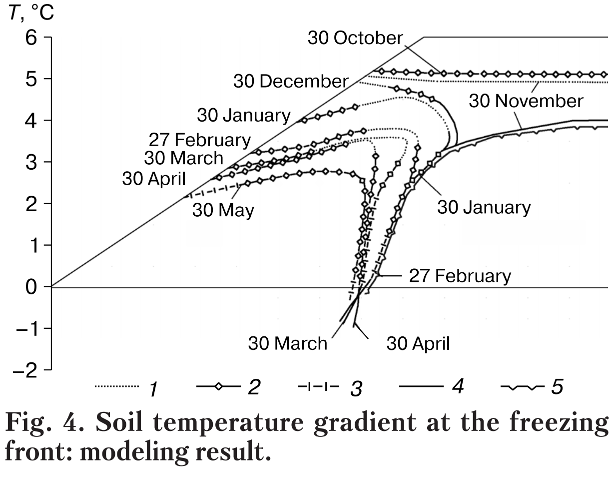

Fig. 4. Soil temperature gradient at the freezing front: modeling result.

1 – >5 °C/m; *2* – 1–5 °C/m; *3* – 0.3–1.0 °C/m; *4* – <0.3 °C/m. Lines show position of freezing front in the embankment in the end of each month during cooling season; *5* – permafrost table.

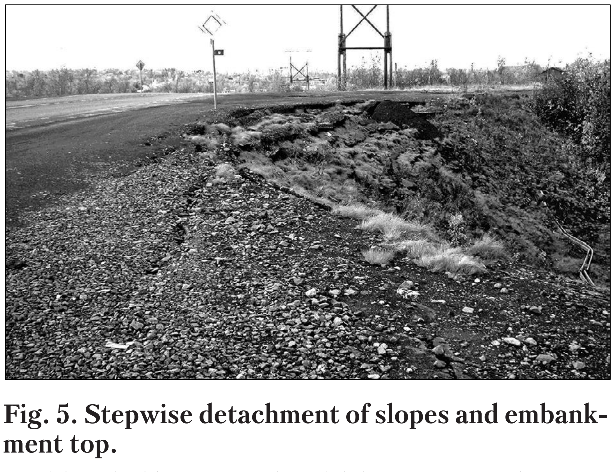

Fig. 5. Stepwise detachment of slopes and embankment top.

Norilsk–Talnakh motor road, 10th kilometer, September 2010.

fine-grained fill at small temperature gradients (from 0.3 to 5.0 °C/m) at a depth of 3 m in the end of the freezing season (Fig. 4) may produce vertical layers of segregation ice. When the ice layers melt, they leave vertical zones of low-density liquefied soil along which ground can subside and slump.

Stepwise detachment of roadbed and slopes is another type of deformation associated with flooding and thermokarst. It results from heterogeneity in bearing capacity of soils exposed to thermokarst which thaw from the slope toes toward the road axis (Fig. 5). Steps may occupy most of the carriage way and their height difference may reach 5–10 cm. Stresses in fill caused by uneven subsidence of soils produce cracks, cause fill slumping, and destroy road pavement.

The mitigation measures should include flattening and reinforcement of slopes, including by setting up benches. The benches made specially to prevent embankment flooding have been used successfully at the roads we studied.

The choice of efficient methods to mitigate slumping is difficult because deformation of this kind often arises in the sides of closed depressions that accumulate snow in winter and water in summer. Building support walls is problematic in this case because it is hard to ensure the required bearing capacity of foundations in areas of thermokarst activity. Natural drainage of such depressions is impeded or barred by the embankment body. Therefore, reinforcement of slopes and stabilization of native soils with thermosyphons appear to be the best workable anti-slumping measures.

CONCLUSIONS

The reported results allow the following inferences:

(1) deformation of motor and rail roads between Norilsk and Talnakh results mostly from thermokarst and flooding effects due to natural (ice-rich low permeable soils) and engineering (few and poorly operated drain systems) factors;

(2) the roads have been operated for several decades, and their deformation progresses, both in number and size of deformed zones along the Norilsk–Talnakh roadway;

(3) there are four main types of deformation common to the area; they all are associated with bearing capacity loss in permafrost foundation soils but differ in combinations of unfavorable factors that destroy the roads; each type of deformation requires specific mitigation measures;

(4) the most efficient ways of increasing road stability include thermal stabilization (cooling) with thermosyphons or reinforcement and creation of drain systems, including drainage of the seasonally thawing active layer.

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