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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

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A NEW WAY FOR THERMAL STABILIZATION OF PERMAFROST UNDER RAILWAY EMBANKMENT

A.A. Zhang[1], E.S. Ashpiz[2], L.N. Khrustalev[1], D.M. Shesternev[3]

[1] *Lomonosov Moscow State University, Geological Faculty, Department of Geocryology,*
1, Leninskie Gory, Moscow, 119234, Russia; zhang.andrew.msu@gmail.com
[2] *Moscow State University of Railway, Institute of Track, Construction, and Structures,*
Department of Track and Track Facilities, 2, Minaevskiy per., Moscow, 127055, Russia
[3] *Melnikov Institute of Permafrost, SB RAS, 36, Merzlotnaya str., Yakutsk, 677010, Russia*

It is suggested to prevent permafrost thawing under railroad embankments by laying a geosynthetic heat insulator on the slopes. The insulation creates a cooling effect whereby the permafrost table moves upward from the embankment base to its body. The thaw depth reduction is confirmed by geophysical surveys at a test segment of a railway operated in a permafrost area. The new method has better economic performance than other known ways of thermal stabilization.

Embankment, subgrade, permafrost, permafrost table, cooling effect, geophysical survey, economic performance

INTRODUCTION

The reported method was suggested in 2008 to mitigate years-long thawing of permafrost under railway and motor roads [*Ashpiz et al., 2008a*]. It consists in laying a geosynthetic heat insulator on embankment slopes, which increases frost depth above the active layer and causes a cooling effect. The geosynthetic insulator is laid under the slope base and is fixed on the slope with metal pins. The method was tested successfully at a segment of the Amur-Yakutsk railway in 2009 through 2016.

THEORETICAL BACKGROUND

The theoretical background of the method was detailed in a previous publication [*Ashpiz et al., 2008b*] and is only sketched in this paper. The behavior of active layer thickness (seasonal frost and thaw depths) as a function of thermal resistance of the ground surface is plotted in Figure 1. Heat transfer conditions change seasonally: the Earth absorbs heat in summer and gives it back in winter. Heat accumulated in summer causes thawing of the active layer and warming of shallow permafrost while winter heat loss causes active layer freezing and permafrost cooling. The ground remains frozen if the annual amount of outgoing heat exceeds systematically that of incoming heat, and the potential winter frost depth h_f (provided that all ground is unfrozen) exceeds the summer thaw depth h_i: $M = \dfrac{h_f}{h_i} \geq 1,$ while permafrost undergoes long-term thawing at $M < 1$. The ratio M of the winter frost depth to the summer thaw depth as a parameter of the ground thermal state was suggested by *Tsytovich* [*1928*]. The way of thermal stabilization discussed in this study aims at reducing the thaw depth on embankment slopes while keeping the frost depth almost invariable. It follows from Fig. 1 that the reduction of thaw depth at increasing low thermal resistance of the slope surface (in summer) is much greater than that of frost depth in the case of high thermal resistance in winter when the slopes are covered with snow. Thus, heat insulation on the slopes increases the parameter M, proportionally to the snow depth. At some thickness of the insulator,

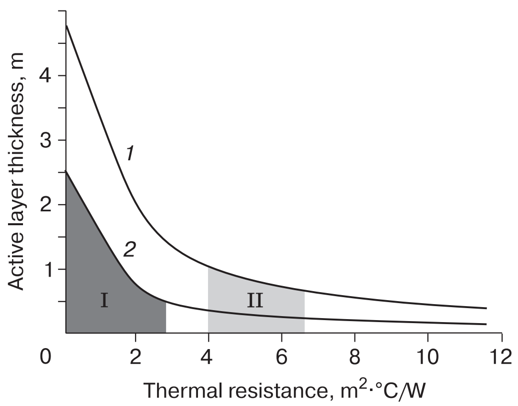

Fig. 1. Active layer thickness vs. thermal resistance of the surface.

1 – freezing; *2* – thawing. Curves I and II refer to zones of higher thermal resistance of slope surface, in warm (I) and cold (II) seasons.

the ratio becomes $M > 1$ and the slope effect on the ground is cooling rather than warming. Cooling is always possible in the presence of snow on the slopes. Note that the insulation efficiency is inversely proportional to the thickness of the insulation. This apparently paradoxical relation is evident in plots for the railroad segment near Anadyr Village (Fig. 1). The parameter M increases markedly from 0.4 to 1.4 when a 10 cm thick geosynthetic insulator (e.g., extruded polysterene foam, XPS) is laid on the slopes. The slopes cause a warming effect on the ground under the embankment in the absence of heat insulation but a cooling effect in the presence of an insulator.

The thickness of the insulator required to achieve a cooling effect was estimated by simulation of thermal interactions between the slope surface and subgrade soil with the WARM software [*Khrustalev et al., 1994*]. The modeling was applied to data from seven weather stations in areas of frequent blowing snow events (Khoseda-Khard, Khatanga, Agatha, Anadyr, Yamask, Salekhard, Palatka) and six stations in frost areas (Markovo, Susuman, Allakh-Yun, Chulman, Irkutsk, and Chukurdakh). The blowing snow and frost areas are classified on the basis of mean winter wind speed: faster or slower than 4 m/s, respectively. The modeling yielded the following correlation relationships between the slope surface temperature and the dimensionless parameter M:

blowing snow areas: $T_{de} = -5.51M + 6.64$ $(n = 56, r = -0.938)$,

frost areas: $T_{de} = -7.76M + 7.68$ $(n = 48, r = -0.957)$,

where T_{de} is the computed ground temperature on the slope surface (mean annual ground temperature at the active layer base), °C; n is the statistical sample size; r is the correlation coefficient.

Thus, the two parameters show high correlation in both cases. (Mind that the correlation is statistically significant when the coefficient magnitude exceeds 0.7.)

EXPERIMENTAL STUDY

The performance of the suggested thermal stabilization method was tested at a 80 m long segment of the Amur-Yakutsk railway (695-th km). The segment is located in a zone of continuous permafrost in the southeastern Siberian craton. Permafrost is as thick as 200 m in the area and has a temperature within −2.0 to −2.2 °C. It encloses thick ice wedges at depths 2–5 m below the ground surface in ⩾10 m thick ice-rich rocks containing 25–63 wt.% of water, with lenticular-layered, massive, and massive-porous cryostructures.

The test railroad segment was a 4.5 m embankment with 7 m wide slopes (1:1.5) and two 1 m high and 2 m wide benches. A 5 cm thick heat insulator (XPS) was laid on the slopes and fixed with metal pins (Fig. 2). The insulation thickness was estimated according to design. The insulator was covered with a 3D plastic geogrid filled with earth containing seeds of perennial grasses, or with a 2D (plane) geogrid and a layer of earth over it.

The original plan implied monitoring of the ground temperatures inside and under the embankment in logged boreholes specially drilled along profiles near the embankment. However, no boreholes were drilled because the railroad was set into provisional operation. Therefore, the depth to the permafrost table was measured by ground penetrating radar (GPR) instead (Fig. 3), run by the Institute of Permafrost (Yakutsk) [*Khristoforov et al., 2016; Shesternev et al., 2017*].

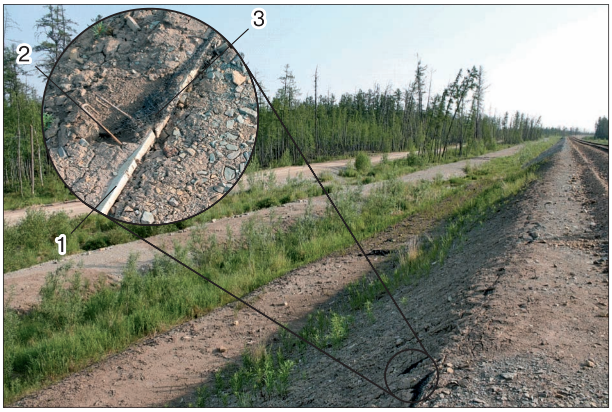

Fig. 2. Test segment, 695-th km of the Amur-Yakutsk railway (photograph by A. Zhang, 2015).

1 – heat insulator (extruded polysterene foam, XPS); 2 – metal pins; 3 – 3D plastic geogrid.

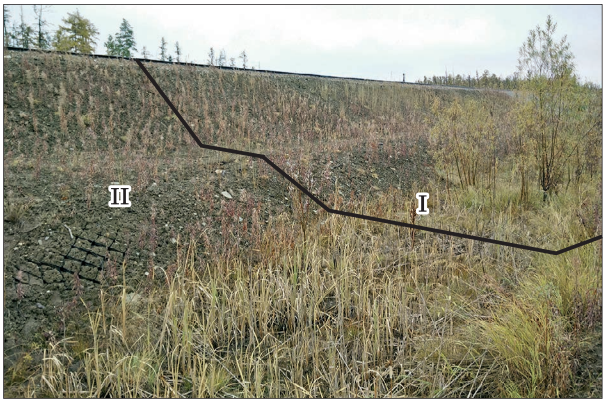

Fig. 3. Location of GPR line (I) at test railway segment.

II refers to slope with heat insulation by an earth-filled geogrid.

Figure 4 shows the position of the permafrost table at the time of testing (2016) according to GPR and its initial position in 2009 according to temperature logging (curves II and I, respectively), as well as its predicted position fro the cases with and without heat insulation (curves IV and III, respectively). The soil and vegetation cover was neglected in the modeling.

The results of geophysical surveys and simulations (curves II and IV, respectively, in Fig. 4 almost coincide), while comparison of curves II and III provides an idea of the method performance.

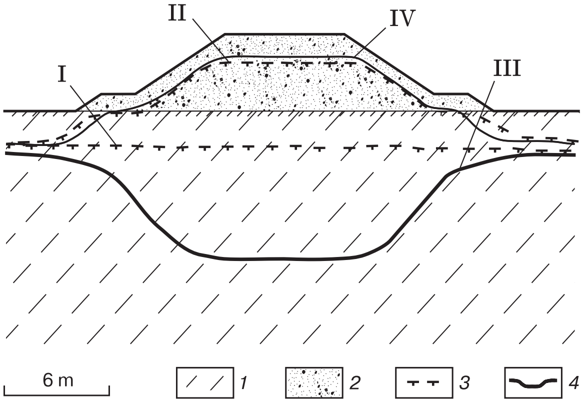

Fig. 4. Permafrost table under and inside the embankment at the test railway segment, prior to construction in 2009 (I) and in July 2016 according to GPR data (II) and modeling (IV and III: with and without insulation, respectively).

1 – silt; *2* – gravel and sand; *3*, *4* – permafrost table, according to field measurements (*3*) and modeling (*4*).

ECONOMIC PERFORMANCE OF THE NEW THERMAL STABILIZATION METHOD

The economic performance of the new thermal stabilization method was compared with that of other methods, such as the use of crush stone or ventilation ducts on slopes and vertical thermosyphons installed on the benches. The constructive parameters of the compared methods were calculated for climate conditions and ground properties at test sites, for 10 m on one side of the track (Table 1).

As one may see in Table 1, the costs of materials for cooling systems increase in the series ‘XPS heat insulation–thermosyphons–crush stone–ventilation ducts’. The costs were estimated with reference to average prices of materials in Russia, according to price lists of producers and providers for 2014–2016. However, evaluation of economic performance requires also the knowledge of transportation and installation costs, which is unavailable for us. At the same time, heat insulation reasonably appears to be the optimal solution because its transportation and installation are the cheapest.

Table 1. **Costs of materials used in different thermal stabilization methods**

No.	Cooling systems	Total volume, m^3		Average price for 1 m^3, RR		Total costs, RR
1	XPS heat insulator laid all along slopes, including benches	5.06		4800		24 288
2	Crush stone laid all along slopes, including benches	91.0		1300		118 300
		Number for 10 linear meters		Costs, RR		Total costs, RR
		ducts	thermosyphons	ducts	Thermosyphons (8.5 m long)	
3	Ventilation ducts* installed all along slopes, including benches (0.3 m, spaced at 0.4 m)	14	–	9400	–	131 600
4	Vertical thermosyphons on benches (radius 0.035 m, length 8.5 m, spacing 1.6 m)	–	6	–	9837	59 022

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* Prices for one duct: 5200 RR for L1-8/2 and 4200 RR for L1d-8.

CONCLUSIONS

1. A new way is suggested for thermal stabilization of permafrost under railroad embankments by means of geosynthetic insulation laid on slopes, which causes a cooling effect in the presence of snow.

2. The new method is advantageous over other known methods in high performance, sustainability, safety, low costs, and simplicity of installation and maintenance.

Broad use of the suggested stabilization method will become a new step forward in technological advance of railroad construction.

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