Using of synthetical thermal insulators for conversation of frozen soil conditions in the base of railway embankment

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ABSTRACT
The design of railway embankment with syntactical thermal insulator on permafrost soil is considered. It is shown that thermal insulator in embankment body allows one to save soils under embankment in frozen condition. It is recommended to put the thermal insulator near the embankment foot in low embankments. The result of analytical calculation and mathematical modeling on the determination of the thermal insulator thickness are given.

1 INTRODUCTION

Railroad embankment significantly changes the conditions of heat exchange between soil and air. The upper part of the embankment surface (subgrade) intensifies the cooling of the ground due to cleaning snow off the surface, and the escarpments, on the contrary, weaken this cooling due to accumulation of snow cleaned off the main area or blown off by wind. In the summer time escarpments also intensify the warming of the soil due to radiant energy which increases because of lower reflecting power of their surface and their angle in relation to the horizon. In case of a particular correlation between the surfaces of the subgrade and the escarpment, the body of the embankment receives more warmth than "cold," and the upper layer of the permafrost soil lowers down at the base of the road bed and more often than not it leads to deformation of the embankment. It is obvious that the warming effect of the escarpment can be neutralized by using thermal insulators which should be laid at a depth of 15-20 cm directly under the paving of the escarpment. It is advisable to use synthetic thermal insulator (for example, Penoplex), which has low thermal conductivity, hydrophobic properties and small mass; apart from that, it is very easy to apply. When the synthetic insulator has certain thickness, the thermal balance becomes negative, the escarpment begins to have some cooling effect on the soil and the foundation remains in the frozen state.

Let us designate the amount of thermal energy outgoing through the subgrade surface as Q_1 and the amount of thermal energy coming in through the escarpment surface as Q_2. The condition Q1+Q2 >0 means warming of the escarpment foundation, and the condition Q1+Q2<0 means its cooling. With strict formulation these conditions can be evaluated only in terms of numbers by means of mathematical modeling of thermal interaction between the embankment and the foundation soil, however with some assumptions analytical evaluation becomes possible. Let us take a closer look at these issues.

2 THEORETICAL CONCEPTS OF THERMAL INTERACTION BETWEEN THE EMBANKMENT AND PERMAFROST FOUNDATION

Let us assume that the intensity of the annual inflow and outflow of warmth through the escarpment surface depends on the difference of potential depths (i.e. the depths which can be reached in the case when the whole body of the soil is either melted or thawed) and the actual depths of seasonal freezing-thawing.

$$q_1=(d_{th,1}-d^*_{f,z})L_v \qquad [1]$$
$$q_2=(d^*_{th,2}-d^*_{f,2})L_v \qquad [2]$$

Where $d_{th,1}$, $d^*_{th,2}$ are the actual and the potential thawing depths on the subgrade and the escarpment respectively, m; $d^*_{f,1}$, $d_{f,2}$ are the potential and actual freezing depth on the subgrade and the escarpment respectively; *Lv* is the specific heat of freezing-thawing of the soil, Wh/m^3.

Since in practice the width of the subgrade and the length of the escarpment are more often than not much greater than the depth of seasonal freezing-thawing, the task of freezing-thawing of soil under the middle of the subgrade or escarpment can be considered as linear and apply Stefan's formula. With this approach inaccuracy is possible only at the edges of these planes (the subgrade and the escarpment) and it will not have a significant effect on the general evaluation of the thermal process and it is confirmed by the results of the numerical solution of the two-dimensional problem using computer (see below).

$$d_{th}=\sqrt{\frac{2\lambda_{th}T_s t_s}{L_v}+(\lambda_{th}R_s)^2}-\lambda_{th}R_s \qquad [3]$$

$$d_f=\sqrt{\frac{2\lambda_f T_w t_w}{L_v}+(\lambda_f R_w)^2}-\lambda_f R_w \qquad [4]$$

Where λ_{th}, λ_f are the thermal-conductivity coefficients for the embankment soil in thawed and frozen state W/(m.℃); T_s, T_w are the average summer or average winter temperatures of the soil surface within the boundaries of the subgrade or the escarpment , ℃; t_s, t_w are the length of the summer and winter periods, h. R_s, R_w are the average summer and average winter thermal resistance against heat exchange on the soil surface within the boundaries of the subgrade or the escarpment m^2°C/W.

$$R_s = \frac{1}{\alpha_s} + R_{ins} \quad [5]$$

$$R_w = \frac{1}{\alpha_w} + R_{ins} + R_{snow} \quad [6]$$

Where α_s and α_w are the thermal exchange coefficients on the surface of the subgrade or the escarpments in the summer and winter periods respectively W/(m^2.°C); R_{ins} is the thermal resistance of the insulation laid on the escarpments or the subgrade , m^2.°C /W; R_{snow} is the winter average thermal resistance of the snow covering the escarpment of the subgrade (the methodology for calculating these values was published in a text book [Khrustalev, 2005].

If we then assume that the depth of freezing-thawing throughout the width of the subgrade or the escarpments is invariable (one more assumption) it becomes possible to estimate the heat flows: $Q_1 = q_1B$ and $Q_2 = q_2L$ (B is the width of the subgrade, m; L is the total length of both escarpments including the berms, m). It is obvious that the aggregate of these heat flows will be equal to the annual amount of energy that comes into (goes out of) the foundation under the embankment through its total surface. By equating this energy to zero we develop the equation which helps us to estimate the necessary thermal resistance of the insulation laid on the embankment escarpments in order to prevent degradation of the permafrost soils.

$$Q_1+Q_2 = 0 \quad [7]$$

Figure 1 shows the graphic solution of equation (7) for three points of the anticipated mainline railroad Tommot-Yakutsk where the height of the embankment (H) is 3.5 m (PK 6710+00), 6.0 m (PK 6711+00) and 9.5 m (PK 6710+50).

It becomes clear that the embankment 3.5 m high does not require thermal insulation of the escarpments, the embankment 6.0 m high needs a thermal insulator 0.7 cm thick and the embankment 9.5 m needs insulation 2.2 cm thick (in our case the thermal insulator is Penoplex synthetic insulator with the thermal-conductivity coefficient of 0.035 W/(m .°C)).

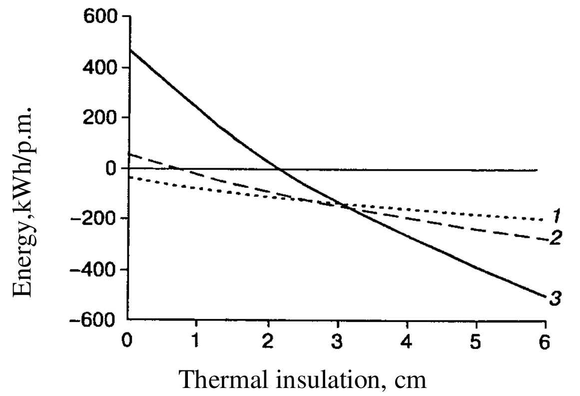

Figure 1. Dependence of the total thermal energy penetrating into the foundation of the embankment on the thickness of thermal insulation on its escarpments: 1 – PK 6710+00, H=3.5 m, L/B = 1.94; 2 – PK 6711+00, H=6.0 m, L/B=3.04; 3 – PK 6710+50, H=9.5 m, L/B=6.72.

On low embankments in order to prevent blowups of the superstructure thermal insulation is often laid on the surface of the subgrade directly under the ballast section. Placing the insulation this way helps to reduce the cooling influence of the subgrade, and the warming influence of the escarpment remains unchanged; under certain conditions it may lead to the positive annual value of energy penetrating into the foundation and, as the result, lowering of the upper boundary of the permafrost soils. Consequently, if the subgrade is covered with insulation it is necessary to cover the escarpment as well.

We need to point out that on Figure 1, curve 3 is steeper than curves 1 and 2. It may take place only if the escarpment itself has some cooling effect. How is it possible?

Figure 2 shows reduction of the seasonal thawing depth (curve 1) and freezing depth (curve 2) under the escarpment as the thickness of the insulation increases for PK 6711+00. Let us note that the thawing is decreasing more rapidly than the freezing. It can be accounted for by the presence of snow cover which cerates additional thermal resistance on the day surface. When the thickness of the thermal insulation is 3.0 cm the depth of thawing becomes equal to the depth of freezing. This means that the escarpment has no thermal effect on the foundation of the embankment. Subsequently, the depth of thawing becomes less than the potential depth of freezing and the escarpment cools the foundation. Therefore, where the thickness of insulation is less than 3.0 cm, the escarpment warms the foundation and in case of greater thickness, it cools the foundation (curve 3). We need to point out that this pattern is only possible with the snow cover and the climatic conditions ensure the values shown on the figures. It is difficult to overestimate its practical significance. It means that it is possible to ensure the frozen state of foundation soils under an embankment of any height using thermal insulation alone irrespectively of the subgrade width.

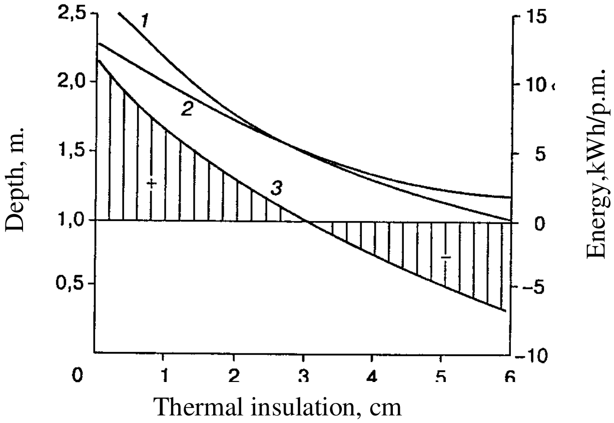

Figure 2. Dependence of the depth of thawing (1) and freezing (2) of the soil on the escarpment and the specific heat energy (3) on the insulation thickness: (PK 6711+00, H=6.0 m, L/B=3.04).

Mathematical modeling of the thermal interaction between the embankment and the permafrost soils of the foundation was carried out with the use of Teplo (Heat) software which was developed by the section for permafrost studies of the Geology Department of Moscow State University [*Software…1994*]. Seven points were selected for modeling on the designed mainline railroad, Tommot-Yakutsk. The purpose of the modeling was to determine the thickness of insulation laid on the surface (into the body) of the embankment in order to stabilize the permafrost conditions in its foundation. The thickness of the insulation was determined by selection which implied solving multiple variants of the problem. The soil profiles and characteristics were obtained from the survey data (Table 1). Data on climatic conditions came from the Yakutsk weather station which is the closest to the analyzed site (Table 2). The results of modeling are shown in Table 3.

Table 1. Survey data.

Type of soil	Depths interval	Heat of phase transition Wh/(m^3)	Thermal-conductivity coefficient W/(m°C)		Volumetric heat capacity		Gravimetric moisture d.e.	Density of dry soil t/m^3	Compressibility when thawed δ, d.e.
			Thawed phase	Frozen phase	Thawed phase	Frozen phase			
Rubble-sandy soil, 55% of rubble (embankment body)		20869,0	1,75	1,98	661,0	531,0	0,11	2,146	0,0
PK 6692+00									
Loam	0,0-1,0	37200,0	1,51	1,68	870,0	650,0	0,25	1,60	0,06
Loam	1,0-2,0	36456,0	1,57	1,66	928,0	650,0	0,28	1,40	0,1
Gravel soil	2,0-3,0	44194,0	1,92	2,4	842,0	614,0	0,27	1,76	0,20
Rubble soil	3,0-55,0	30634,0	2,26	2,62	773,0	628,0	0,18	1,83	0,05
PK 6710+00,6710+00*									
Icy loam	0,0-2,5	55800,0	1,72	1,90	951,0	603,0	0,6	1,00	0,45
Loam	2,4-4,5	49104,0	1,57	1,80	858,0	586,0	0,48	1,10	0,29
Pulverescent sand	4,5-55,0	28644,0	1,91	2,14	766,0	568,0	0,22	1,4	0,05
PK 6710+50									
Loam	0.0-1.0	44640.0	1.68	1.86	969.0	684.0	0.30	1.60	0.1
Loam	1.0-2.5	55800.0	1.72	1.90	951.0	603.0	0.60	1.00	0.45
Loam	2.5-5.0	51150.0	1.57	1.85	855.0	586.0	0.50	1.10	0.30
Clay sand	5.0-5.5	32550.0	1.33	1.51	766.0	568.0	0.25	1.4	0.10
Pulverescent sand	5.5-55.0	32550.0	1.91	2.14	766.0	568.0	0.25	1.4	0.04
PK 6711+0, 6711+00* (The asterisks indicate points which correspond to the original longitudinal profile of the railroad)									
Plastic clay sand	0.0-1.5	23320.0	1.28	1.65	599.0	458	0.15	1.60	0.05
Fluid loam	1.5-3.5	39897.0	1.45	1.57	838.0	605.0	0.30	1.43	0.15
Fluid clay sand	3.5-4.0	31620.0	1.68	1.80	772.0	627.0	0.20	1.70	0.10
Rubble sand	4.0-5.5	44640.0	1.57	1.80	860.0	587.0	0.4	1.2	0.42
PK 6728+00									
Loam	0.0-1.4	44600.0	1.68	1.86	964.0	684.0	0.30	1.60	0.10
Loam	1.5-2.0	42966.0	1.57	1.66	928.0	650.0	0.33	1.4	0.15
Pulverescent sand	2.0-3.5	32550.0	1.91	2.14	766.0	568.0	0.25	1.40	0.08
Clay sand	3.5-55.0	32550.0	1.39	1.51	766.0	568.0	0.25	1.4	0.07

Table 2. Climatic conditions.

Parameter	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
T_e, ^0C	-42.0	-35.6	-22.0	-6.8	6.2	15.6	18.8	14.9	6.1	-7.9	-28.2	-39.5
Q, Вт/м^2	14.34	44.6	122.7	189.6	215.1	240.5	229.4	168.9	105.1	52.6	20.7	7.97
V, mps	1.4	1.4	2.0	2.8	3.4	3.3	3.0	2.8	2.6	2.6	2.0	1.3
h_s,m	0.23	0.27	0.28	0.17	-	-	-	-	-	0.05	0.14	0.17
ρ_s, gr/cm^3	0.15	0.16	0.17	0.20	-	-	-	-	-	0.12	0.13	0.14

Note: T_e is the temperature of the air; Q is the total sun radiation; V is the wind velocity; hs is the height of the snow cover; ρs is the snow density.

Table 3. Mathematical modeling results.

PK	H, m	B, m	L, m	L/B	Thermal insulation thickness, cm	
					At the embankment foundation	On the escarpment surface
6692+00	2.0	6.5	7.2	1.11	12	0
6710+00	3.5	6.5	12.6	1.94	4	0
6728+00	5.0	6.5	18.0	2.77	0	5

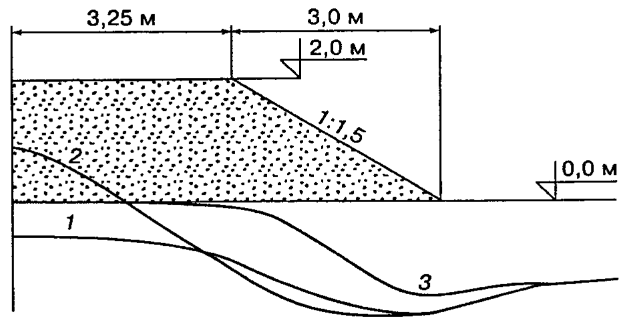

Figure 3. The position of the upper boundary of the permafrost soils in the body and foundation of the embankment at the end of summer season 50 years after its construction (PK 6692+00, H=2.0 m, L/B-1.11): 1 – embankment without thermal insulation, 2,3 – embankment with 12 cm insulation laid horizontally (2 – on the surface of the subgrade covering all its width, 3 – at the height of 0.3 m from the embankment footing covering all its width).

The results of modeling show that where the height of the embankment is 3.5 m (PK 6692+00 and PK 6710+00), the seasonal thawing reaches below the embankment footing (Figure 3, curve 1). Thermal insulation laid on the surface of the subgrade significantly restricts thawing along the center line of the track but does not reduce it throughout the whole subgrade (see Figure 3, curve 2). Only the thermal insulator laid at the embankment's footing gives the desirable effect i.e. keeps the subgrade foundation soils frozen (see Figure 3, curve 3).

The embankments with the height over 3.5 m do warm the foundation but, as Figure 4 shows, this warming disappears absolutely if a thermal insulator 2-6 cm thick is laid along the escarpments of this embankment (see Table 3).

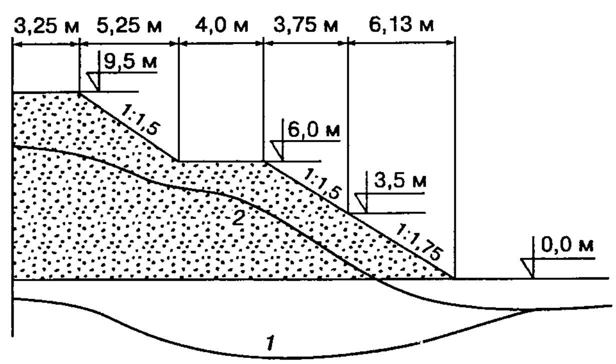

Figure 4. The position of the upper boundary of the permafrost soils in the body and foundation of the embankment at the end of summer season 50 years after its construction (PK 6710+50, H=9.5 m, B=6.5 m, L=39.7 m): 1 – embankment without thermal insulation, 2 – embankment with 4 cm thick thermo insulation laid under the paving of the escarpment throughout their length.

Figure 5 shows the dependence of thickness of insulation necessary for keeping the foundation soil in frozen condition upon the ratio of the total length of the escarpments and berms to the width of the subgrade. It is evident that as this ration increases the thermal insulator thickness also increases. It corresponds to our theoretical concept about the warming influence of the escarpments and the cooling influence of the subgrade. As the warming surface increases (escarpments and berms), if the cooling surface (the subgrade) remains the same, there is the need for greater thermal resistance of the thermal insulation on the escarpments to maintain the frozen condition of soil in the embankment foundation. In our opinion it is self-evident. What is not evident today is the reduction of the thickness increase rate after a certain value (conventionally we call it critical), is reached as the said ratio of embankment surfaces are increasing.

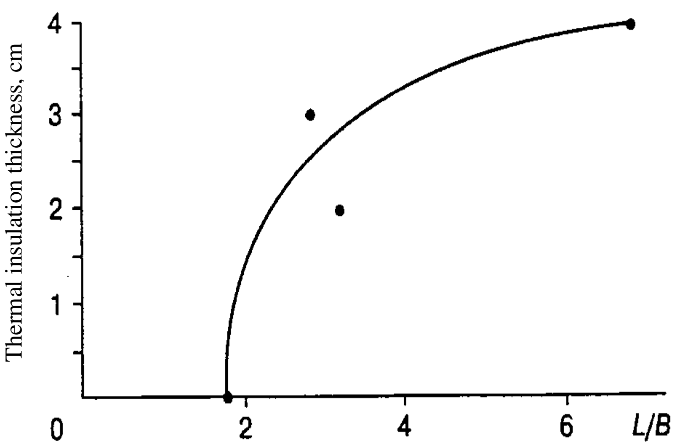

Figure 5. The dependence of on the ratio of embankment surfaces. Dots are the result of modeling.

This circumstance can be accounted for only by the fact that the escarpment covered with the thermal insulator with the thickness exceeding the critical has a cooling influence on the embankment foundation soils as it was mentioned above. Thus, mathematical modeling of thermal interaction between the embankment and the permafrost soils of the foundation, on the whole, confirms our theoretical concept about this interaction.

3 CONCLUSIONS

Synthetic thermal insulation laid in the embankment helps to regulate the temperature conditions of the embankment soil and the underlying permafrost foundation soils. In case of a low embankment the thermal insulation shall be laid near the embankment footing to cover its full width and prevent penetration of the seasonal thawing boundary into the permafrost foundation. In case of high embankment the thermal insulation shall be laid under the pavement of both escarpments and berms throughout their length to ensure the permafrost condition of the foundation soils. To avoid degradation of the foundation permafrost soils, it is not recommended to apply laying the thermal insulation under the ballast section which is so widely used today.

The thickness of the thermal insulation is determined on the basis of mathematical modeling of the interaction between the embankment and the foundation soils or analytical calculations. For low embankments it depends on their height and decreases as the height grows. For high embankments the thermal insulation thickness depends on the ratio between the total length of the escarpments and berms and the width of the sub grade, it grows as the ratio increases.

The warming influence of the escarpment on the foundation soils decreases with the growth of the thermal insulation thickness and after reaching the critical thickness (the insulation thickness with which the depth of the seasonal thawing on the escarpment equals the potential depth of seasonal freezing) the escarpment begins to have a cooling effect. It allows to ensure the frozen condition of the foundation soil of embankment with any height irrespectively of the subgrade width by only laying thermal insulation without using additional means for cooling (e.g. rockfill, air channel, thermal siphons, etc.).

4 REFERENCES

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