Operational ability of road transport structures in complex hydro geological conditions

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Abstract. Working capacity of traffic facilities in the northern European part of Russia depends on difficult natural climatic conditions. It means deep frost penetration and high ground-water level. Both two factors considerably impact on the amount of frost boil of soils in the roadbed. Because of the analysis of a water-and-thermal regime of soil it is possible to detect it’s characteristic, to adjust initial and boundary conditions in the performance of theoretical tasks based on laws of thermodynamics for description of migration process of heat and damp in the road bed. A solution was found with a numerical inversion of Laplace transformation. Realization of that task makes possible to forecast dampness to the end of winter period and to determine the amount of frost boil of soils. To avoid subgrade deterioration in this period the temporary axle load limitations on public roads are imposed.

1. Introduction

The efficiency of road transport and social-economic development of the region essentially depends on the technical condition of the whole road network of the Arkhangelsk Region. The main arterial route through the region that connects Moscow with the northern part of Arkhangelsk and carries important commercial traffic is the federal road M8 “Kholmogory”. It has a total length up to the Vologda Region border of 533 km. The average annual daily traffic varies on different sections from 700 to 6000 vehicles per hour.

The experience of road operation in conditions of the Russian North shows that despite observance of all ruling specifications and other normative documents when designing and constructing roads, the pavements deteriorate prematurely. The length of public roads that are in poor condition is annually reported to exceed 20%. To a great extent this could be explained by the complex climatic and hydrogeologic conditions of the region [1].

The considerable extent of the region from north to south means that the climate varies. The average temperature in the south-western districts is higher than in the north-eastern ones. The relative humidity of air is 70…90%. According to the index of moisture conditions the Arkhangelsk region belongs to the humid zone: total annual precipitation exceeds by more than 100 mm the evaporation. In these conditions the infiltration of precipitation provides accumulation and storage of groundwater that has produced swamps on flat terrain and generally high water-tables. Ground water is the major source of moisture of subgrade soils and underlying ground. The main underlying soils are moraine loams covered
with sandy loam, sand and light loam layers 0.25 to 1.5 m thick. With such soil profiles results in that not only road subgrade soils but also the layers below are affected by seasonal freezing and that affects the magnitude of frost heave. The lacustrine silt deposits in many areas have a low permeability that promote high water tables [2].

2. Materials and Methods
The most typical road sections provided with special radiometric equipment (downhole gamma density and neutron moisture indicator). That allowed measuring the frost heave of subgrade and underlying soils, water table, depth of frost penetration, soil density and moisture content all day round, were selected for studies related to the effect of climatic conditions on the operational capacity of roads.

As a result of the study the peculiarities and regularities of water table variations (i.e. autumn/spring highest points in the curve and winter/summer lowest points).

When snow starts to melt (April - May) the spring ground water table rise takes place within 10…20 days while the highest autumn peak lasts two months (September - October) that contributes to wetting up of the subgrade soil [3, 4].

The common character of variations of ground water level in a year cycle is practically the same for central and northern districts of the Russian road-climatic zone II.

Nevertheless, there exist some peculiarities in the ground water regime:
– in the annual cycle the water table is higher in the northern districts;
– the spring rise of water table comes 1 to 1.5 months later in the north;
– in winter ground water level subsidence reaches 0.8…2.0 m in the north and only 0.4 m in the southern part of the II road climatic zone.

The analysis of the annual cycle of the water-heat regime of subgrade shows that the greatest danger for the pavement structure stability is considered to be the autumn ground water level. It is precisely the time when due to high water table a significant wetting up of soils takes place. In autumn moisture content of soils increases 1.4…1.6 times.

The severe climatic conditions in combination with mainly flat relief of terrain, silts and high water table contributes to accumulation of moisture in subgrade soils, deep seasonal freezing and intensive frost heave [5].

Soil distortion when freezing can result in serious damages to the road pavements. The most damaging is differential (changeable) heave that take place longitudinally and at different depths of the frozen layer. It disturbs the stability of the subgrade and impairs performance of the road pavement [6].

3. Results
Researches that have been on-going during seven winter periods [7] showed that the average magnitude of frost heave of subgrade 1.5…3. times exceeded value allowed for the asphalt pavements [2] (see figure 1).

![Figure 1. Frost heave of the subgrade soils (section 4)](image_url)

High variations of frost heave values of subgrade soils were obtained in different winters for low embankments. Long-term observations were made in extreme climatic conditions when in some winters the duration of sub-freezing air temperatures (Freezing Index) varied from 1250 to 2230 degree-days; average: 1539 degree-days.
Figures 2, 3 show the results of road surface frost heave measurements in longitudinal and cross sections for one of the winter periods. Figure 4 represents the dynamics of frost heave of subgrade soils for seven winters. Above data testify that from the middle of October until early March the most intensive frost heave of subgrade and underlying soils occur. For this period raising of road pavement exceeds 70…90% total frost heave for the whole winter period, freezing speed decreases 2…2.5 times. By the end of March, frost heave reaches its peak point and depends on:

- types of soils lying in freezing area
- water table and initial (autumn) moisture content
- air temperature that determines freezing speed and water migration in soils [8-10].

Water-heat regime study allows defining of its peculiarities for the study area and also more precise initial and boundary values when solving engineering problems.

4. Discussion

Experimental research shows that in autumn moisture content of subgrade soils exceeds 0.7Wm. Therefore liquid phase of water plays significant role in migration process [11-15]. Than time-varying process of heat and water interchange in subgrade may be presented by the following system of differential equation of partial derivatives:

For the frozen zone: \(0 \leq Z \leq Z_o\)
\[
\frac{dt_f}{dT} = a_f \frac{d^2 t_f}{dZ^2};
\]  
(1)

\[
\frac{dW}{dT} = a_{wf} \frac{d^2 W}{dZ^2} + a_{wf} b_{wf} \frac{d^2 t_f}{dZ^2};
\]  
(2)

For the melted zone: \((0 \leq Z \leq H)\)

\[
\frac{dt_m}{dT} = a_m \frac{d^2 t_m}{dZ^2};
\]  
(3)

\[
\frac{dW}{dT} = a_{wm} \frac{d^2 W}{dZ^2} + a_{wm} b_{wm} \frac{d^2 t_m}{dZ^2};
\]  
(4)

Where \(t_f, t_m\) – temperature of frozen and melted soils respectively;  
\(T\) – time of freezing;  
\(Z\) – depth;  
\(a_f, a_m\) – thermal diffusivity of frozen and melted soils;  
\(awf, awm\) – hydraulic conductivity of frozen and melted soils;  
\(W\) – soil moisture content;  
\(Bwf, bwm\) – thermal gradient coefficients.

Solution of equations (1-4) was obtained by using Laplacian numerical inversion for the following initial and boundary conditions:

– temperature of subgrade soils before freezing starts is constant, \(t(0,) = t_\infty\);  
– subgrade soil surface temperature during period of freezing is equal to average value for the whole winter season, \(t(T,0) = t_0\);  
– initial moisture distribution varies by depth, \(W(0, Z) = \sum \Delta W_i U(Z - Z_i)\);  
– moisture content in the freezing interface in frozen zone is more than in melted zone by value \(A\), i.e. \(W(T, Z_0) = W_m(T, Z_0) + A\).

The total water content in the layer \(0 \leq Z \leq H\) (high water table) and \(0 \leq Z < \infty\) (low water table) is constant, i.e. water content intake from the melting zone is equal to increase of water in frozen area [16].

For \(0 \leq Z \leq H\)

\[
\int_0^H \left[ W(T, Z) - \sum_{i=1}^N \Delta W_i U(Z - Z_i) \right] dZ = \int_0^H \left[ \sum_{i=1}^N \Delta W_i U(Z - Z_i) - W_m(T, Z) \right] dZ
\]  
(5)

For \(0 \leq Z < \infty\)

\[
\int_0^{Z_0} \left[ W(T, Z) - \sum_{i=1}^N \Delta W_i U(Z - Z_i) \right] dZ = \int_{Z_0}^H \left[ \sum_{i=1}^N \Delta W_i U(Z - Z_i) - W_m(T, Z) \right] dZ
\]  
(6)

Created and applied computer program allows to determine moisture content of soil for given interval \(\Delta Z\) layer by layer to the maximal depth of frost penetration by the end of winter.

The results of calculations correlate well with the experimental data for different road sections.
Forecasting of moisture content by the end of winter period permits to define variations in moisture content comparing with the initial (autumn) distribution and also value of frost heave using the formula below:

\[ h = 1.09 \sum_{i=1}^{N} (W_{zi} - W_{oi})Z_i + 0.09 \sum_{i=1}^{N} (W_{oi} - W_{pi})Z_i, \]  

where \( W_{zi} \) – moisture content by the end of winter period; 
\( W_{oi} \) – moisture content before freezing starts.

The first summation in equation (7) expresses magnitude of frost heave due to the expansion of migration water during the whole freezing period. The second one defines magnitude of frost heave due to freezing of initial water.

The forecasted magnitude of frost heave for typical soils and for conditions of the Arkhangelsk region is 12 cm, that is practically 3 times more than allowed.

Variable (differential) frost heave and winter moisture accumulation of subgrade soils is dangerous for roads in spring. It contributes in cracking and other deformations of pavement (see figure 5).

It has been defined that the process of deterioration includes the following: in the first two years after the road was completed (1986) micro cracks started to appear, these cracks progressively developed each year for the next 2 years and a net of cracks then formed, the fifth year of operation was characterized by progressive deterioration, and commencement of potholing due to plucking of pieces of asphalt from the pavement surfaces.

At the moment the road “Kholmogory” is in unsatisfied condition, actual road structural strength is only 66 to 90% of the E-modulus required by Russian standards. The maximal decrease of road surface strength occurs in spring when thawing of the upper layers of subgrade soils starts (positive temperatures), but the lower layer is frozen and there is no possibility for drainage through frozen layers. Above the frozen zone water accumulates under the road structure.

To avoid subgrade deterioration in this period the temporary axle load limitations on public roads are imposed. The duration of limitation period depends on climatic conditions of the region.

5. Conclusions
The research made on the important Federal road Moscow to Arkhangelsk described in this paper provides:
– an understanding of the complex mechanisms of heat and water migration below road pavements in the extended seasonal freezing conditions typical of the region of Arkhangelsk;
– Clarification of the boundary conditions when solving theoretical problems of a means of forecasting the soil moisture content and frost heave;
– to evaluate the operational condition of the road;
– to work out recommendations on elaboration of norms for road design;
– evidence to justify improving the quality of construction of main roads to restrict heave to values less than the limits specified in Russian standards;
– to assign necessary repair works to improve the quality of road pavements.

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