Influence of Ground Ice Content on Thawing Depth Road Base

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Abstract. One of the important parameters that determine technical solutions in the design of roads in the permafrost zone is the depth of thawing of the road foundation soils. The aim of the work was to quantify the degree of influence of the ice content in the soil foundations of roads in the permafrost zone on the depth of their seasonal thawing. For the analysis, we used the classical formula for calculating the thawing depth for bodies of plane symmetry, obtained by solving the single-phase Stefan problem. The results of numerical calculations are presented in the form of 2D and 3D graphs, which make it possible to visually assess the effect of ground ice content and the degree of its change during the road operation period on the depth of thawing of the road foundation. It has been established, in particular, that the degree of change in the depth of thawing at the same value of the increase in ice content in different ranges (for example, from 10 to 20% and from 30 to 40%) for the considered typical case of the ground base of the permafrost zone, decreases by almost 1.3 times. It is shown that the greater the initial ice content of the soil, the lower the degree of decrease in the thawing depth when the ice content changes by a constant value.

1 Introduction

Exploitation of automobile roads in the perfmafrost zone is complicated by many reasons. Among them is the dependence of soil toughness on temperature and on natural or artificial moisture level (ice content) within the active layer of the soil forming the road foundation [1-3]. As is noted in [4-5], the artificial moisturization of the active layer of the soil has the greatest role. For this reason, when designing automobile roads, it is necessary to know not only the natural moisture level (ice content) of the road foundation soil, but also the degree of its change during the exploitation of the road. Among the main parameters considered when designing structures interacting with the soils or the rocks of the perfmafrost zone is the thawing depth [6-8]. This applies also to design of automobile roads in the perfmafrost zone [9-10].

The purpose of this research is to conduct a quantitative assessment of the impact of ice content within the road foundation soil in the perfmafrost zone on the seasonal thawing depth.

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2 Methods

To achieve this aim, a well-known formula to determine the soil thawing depth [10-12] will be used. The initial temperature will be equal to the ice melting temperature.

$$S = \sqrt{\frac{2\tau t\lambda}{\rho L\omega}} \quad (1)$$

Where τ is the duration of the warm period of the year, s; λ is the thermal conductivity coefficient of the thawed soil, W/mK; t is the average air temperature over the thawing period, °C; ρ is the soil density, kg/m^3; L is the latent heat of ice melting, J/kg; ω is the moisture level (ice content) of the soil, unit fractions.

This formula omits the amount of heat going towards heating the frozen soil from its natural negative temperature to the ice melting temperature. In [11], we assessed the permissibility of this omission in forecasting thawing depth of the rocks in underground structures of the perfmafrost zone. It was shown that in most practically relevant cases, the use of formula (1) does not to lead to errors greater than permitted in engineering practice (usually, around 10%). Thus application of the formula is appropriate for the aims of this research.

For convenience, a parameter β will be introducted. It signifies the degree of change in the thawing depth of the active later of road foundation soil as the moisture level (ice content) changes over the period of the road exploitation.

$$\beta = \sqrt{\frac{\omega_1}{\omega_2}} \quad (2)$$

Where ω_i is the moisture level (ice content) of the soil, natural (i = 1) and artificial (i = 2), unit fractions.

Formula (1) uses time expressed in seconds, which is not very convenient in calculating the seasonal ground thaw. Thus, considering that the latent heat of ice melting for the considered case is 335.0 kJ/kg, the formula (1) will be transformed into form:

$$S = 4\sqrt{\frac{Nt\lambda}{\rho\omega}} \quad (3)$$

Where N is the number of months in the warm period of the year

3 Results and discussion

Variant calculations using the presented formulas were conducted. Their results are presented in the form of 2D and 3D charts in the figures 1-3. On the figure 1 is presented the dependence of the thawing depth for a typical perfmafrost zone soil with a density of 1600 kg/m^3 and a thermal conductivity coefficient of 1.4 W/mK on the ice content for various climatic zones. The characteristics of the climatic zones are expressed as the duration of the warm period of the year multiplied by the average air temperature Nt, month × °C.

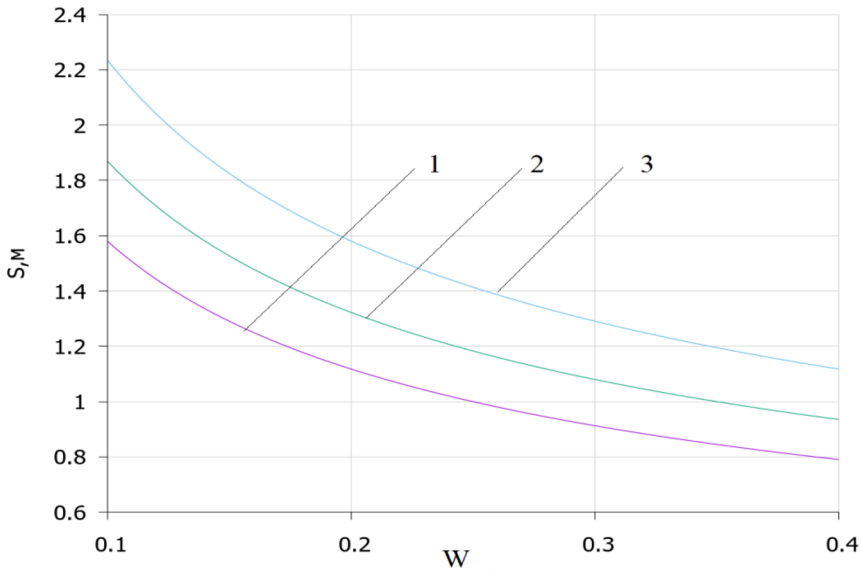

Fig. 1. Thawing depth of the road foundation soil depending on ice content W (unit fractions) for various values of the complex Nt (month × °C). 1 - 25.0; 2 - 35.0; 3 - 50.0.

From the charts it can be concluded that irrelevant of the climatic zone where the road is located, the thawing depth increases along the entire range of ice content change as the ice content in the soil increases. The smaller the range of the ice content change, the stronger the dependence of thawing depth on ice content. It is indicated by the form of the curves on figure 1 and the quantitative analysis. For example, for the case Nt = 25 (curve 1 in the figure), when the ice content changes from 0.1 to 0.2, an increase by 0.1, the thawing depth increases 1.4. times. But when the ice content changes from 0.3 to 0.4, also an increase by 0.1, the thawing depth increases by 1.15 times, which is almost 1.3 times lower.
Figure 2 contains 3D charts which demonstrate this regularity (consider the area of the blue and brown colors on the second chart).

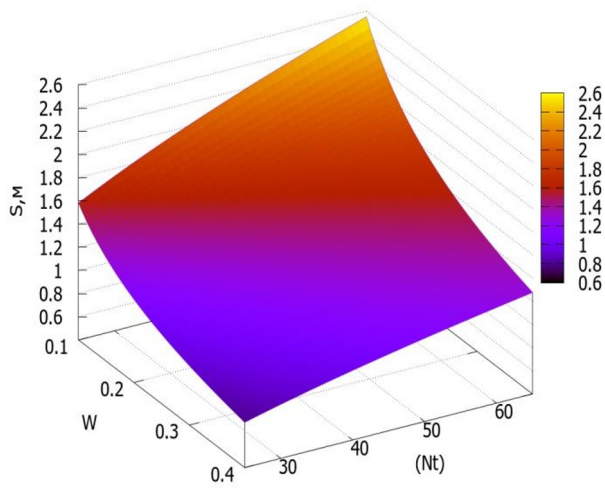

Fig. 2. The thawing depth of road foundation soil depending on ice content W (unit fractions) and climatic characteristics of the warm period of the year (values of the Nt complex, month × °C)

The conclusion is also supported by a quantitative analysis of the calculation formula. The results of the analysis are presented in a table.

Table 1. The degree of change in the soil thawing depth at various ranges of increases in its ice content.

Range of ice content increase	0.1 – 0.2	0.2 – 0.3	0.3 – 0.4	0.4 – 0.5	0.6 – 0.7	0.7 – 0.8	0.8 – 0.9
Degree of change in thawing depth	1.41	1.22	1.15	1.12	1.08	1.07	1.06

The data in the table shows that the higher the initial ice content, the lower the degree of decrease of thawing depth at a change of ice content by a constant value (in the case, 0.1). Figure 3 presents a 3D chart of dependence of the parameter β describing the degree of change in the thawing depth of the active later of the road foundation soil at a change of ice content during the road exploitation.

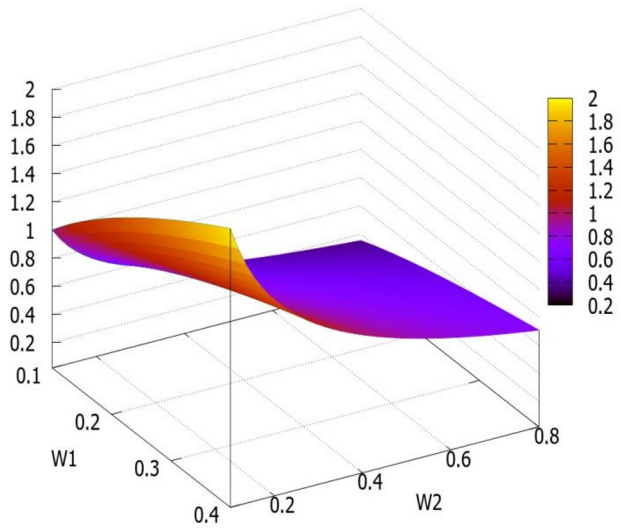

Fig. 3. Degree of change in thawing depth of the active layer of road foundation at a change of ice content from W_1 to W_2 over the period of road exploitation.

Additionally to demonstrating previously described regularities, the chart also allows to assess the degree of change in thawing depth at both a possible increase in ice content over the exploitation period of the road and in cases that the ice content decreases, for example if the soil becomes drier. Having a chart allows to assess the possible variants and to choose a proper, justified technical solution when constructing roads in the perfmafrost zone. For example, to justify the need to use a special thermal protection layer in the road structure [13-15].

4 Conclusion

The influence of moisture level (ice content) in automobile roads foundation soils in various climatic zones on the change of the soil's thawing depth during the warm period of the year was researched. The results of quantitative calculations were presented in the form charts and a table, allowing to assess the impact of ice content and the degree of its change during the exploitation of the road on the thawing depth of the road foundation. It was determined that the degree of change in thawing depth at an increase of ice content by a constant value, for example from 10% to 20% and from 30% to 40%, for a considered typical case of a soil foundation in the perfmafrost zone, decreases by almost 1.3 times.
It was shown that the higher the initial ice content of the soil, the lower tha degree of change in the thawing depth at a change of ice content by a constant value. A 3D chart was created to determine the thawing depth of the active layer of road foundation soil within a wide range of possible changes in ice contant during the exploitation of the road. Having a chart allows to quickly assess the possible variants of change in thawing depth and to choose a proper technical solution during the road design. For example, to justify a need for using a thermal protection layer within the road structure.

The article is relevant for engineers in the road construction sector and for researchers in the area of geocryology. It may also be useful for graduate students in the natural sciences and civil engineering. Further development in this area should be directed towards research of the influence of moisture (ice content) in the dispersed rocks on the thawing depth of the road foundations, considering the dependence of density and thermal conductivity on ice content.

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