Road foundation thawing at change in ice content along the active layer depth

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Abstract

The seasonal temperature and humidity regime of the road foundation in the active layer of soil largely determines the reliability and safety of the automobile road use. The aim of this article is a quantitative assessment of the influence of variation in ice content in the active layer of the road foundation soil in the permafrost area on the depth of seasonal soil thawing. Analytical solutions of one-phase flat Stefan problem at varying ice content along the coordinate were obtained. The solution is in the dimensionless form as a Fourier function based on Stefan number and dimensionless simplexes. The dependence of ice content change on the distance was assumed to be linear. Calculations using the obtained formulas were conducted, comparing against formulas assuming that ice content is a constant. It was determined at which ice content gradient averaging the ice content does not lead to an error greater than permitted in engineering practice. The results of variant calculations are presented as 2D and 3D charts to assess the influence of the initial ice content in the soil and the degree of its variation over the period of road use on the thawing depth of road foundation.

Keywords: automobile road, permafrost, forecasting, thawing depth, ice content, error, averaging, soil, temperature, thermal conductivity

1 Introduction

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2 Methods

\[ W(x) = a + bx \]

\[ W_{x=0} = W_0 \]

\[ W_{x=\delta} = W_k \]

\[ W(x) = W_0 + (\text{grad } W) \cdot x \]

\[ \text{grad } W = \frac{W_k - W_0}{\delta} \]

\[ \bar{g} = \frac{W(x)}{x=\delta} = W_0 + \frac{W_k - W_0}{\delta} \cdot \delta \]

\[ W(x) \frac{ds}{d\tau} = -\frac{\lambda}{\rho L} \frac{\partial T}{\partial x} \]

\[ \frac{\lambda}{\rho L} \frac{\partial T}{\partial x} \]

\[ Fo = St[3S^2 + 2S^3 (W - 1)]/6 \]
The following parameters are used in the expression:

\[ Fo = \frac{a \tau}{\delta^2} \quad St = \frac{L W_o}{C_p t} \]

\[ St'' = \frac{L W_k}{C_p t} \]

\[ S = \frac{s}{\delta} \]

\[ W = \frac{W_k}{W_o} \]

Here \( Fo \) is the Fourier criterion, \( St \) is the Stefan number (criterion), \( \delta \) is the typical depth, \( m \), \( C_p \) the total heat capacity of the soil, \( J/kgK \), \( a \) is the thermal diffusivity coefficient of the soil, \( m^2/s \), \( s \) is the thawing depth, \( m \).

If the parameter \( W \) is larger than 1, the ice content increases with depth. If it is smaller than 1, the ice content decreases with depth. Using equation (6), an assessment of the influence of the change in ice content on thawing depth of the road foundation was made. If the parameter \( W \) is equal to 1 (the ice content is independent of depth and is constant), the equation (6) is transformed into the standard Stefan formula to determine the thawing depth of the soil at an initial temperature equal to the ice thaw temperature.

\[ Fo = \frac{S^2 St}{2} = \frac{S}{\sqrt{2Fo/\delta}} \]

\[ e = \text{abs}[2S(W - 1)/3] \cdot 100\% \]

\[ W = 1 - \frac{0.15}{S} \]

3 Results and Discussion
Fig. 1. Dependence of the Fourier criterion on the Stefan number at given dimensionless thawing depth of the sol for various values of the parameter $W$: 1 – 1.2, 2 – 1.0, 3 – 0.8.

Fig. 2. Change in Fourier criterion depending on the parameter $W$ and the dimensionless thawing depth of the soil at various Stefan number values.

Analysis of the chart shows that at a proportional increase or decrease of the parameter $W$, the degree of change in the Fourier number is the same, but in absolute numbers it significantly depends on the Stefan number. The figure 3 shows the change in error in calculation of soil thaw time to a given depth calculated using formulas (6) and (7).
Fig. 3. The error in determination of the Fourier criterion, when not accounting for variation in ice content along the depth of the soil, for a given temperature for various values of the parameter W. The shape of the plane in the chart shows that for some cases of ice content variation with depth, the calculation error can be significant. As the ice content increases with depth, the thawing depth of the soil is underestimated and if the ice content decreases with depth, the thawing depth is overestimated. Figure 4 shows the relationship between the parameters W and S which guarantees that the error occurring in calculation of the thaw duration to a given depth will be lower than the permitted 10% error.

Fig. 4. The permissible ratio of the parameters S and W which secures that the error in determination of the Fourier criterion will be within permissible range. Surveying the chart, it is visible that the higher the parameter S, the smaller the parameter W should be. This regularity is significant for dimensionless thawing depth smaller than or equal to 1. The character of the curves in the chart signifies that for greater thawing depths, the variation in ice content along the depth of the active layer should be accounted for even with low ice content gradients.
4 Conclusion

An analytical solution of a single-phase Stefan problem at boundary conditions of the first kind accounting for the ice content gradient at depth of the active layer of the soil was obtained. A comparison of thawing depth calculation using the obtained formulas with the results obtained assuming that the ice content in the active layer of the soil is a constant was done. An equation to determine the relative error in determination of the thawing depth of the road foundation soil when averaging the ice content along the depth was obtained. A permissible ice content gradient at which the calculation error does not exceed the allowed error when calculating the thawing depth was determined. The article has both research and methodological relevance and revels and algorithm to assess the influence of averaging individual initial parameters on the final calculation result used to select technical solutions. In this case, the method of assessing the influence of averaging the ice content in the soil on the thawing depth of the road foundation is presented. The article can be of interest for permafrost engineering researchers and civil engineers designing structures in the permafrost area. The method of achieving the specific aim formulated in the article can also be useful for students of construction engineering and geology. Further research should be directed to surveying the influence of non-linear ice content distribution in the soil on the accuracy of thawing depth forecasting.

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