# 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 in determination of the thawing depth. 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

The seasonal temperature and humidity regime of the active layer of the soil largely determines the reliability and safety of engineering structures in the permafrost area because the strength of the frozen soil is dependent on the temperature and ice content (moisture). The works [1-3] contain the results of research of the impact of change in moisture regime of the soil on the reliability of linear engineering structures in the permafrost area. Similar research is presented in [4-6] for automobile roads and railways in the northern regions of Russia and China [7-9]. This field receives significant attention because of its practical relevance for the construction of new oil and gas pipelines in the permafrost area in regions with complicated geocryological conditions [10-12]. The work [13] includes an analysis of key works of subject experts such as S. S. Vyalov, N. A. Tsytovich, I. N. Votyakov, D. Anderson, O. Andersland and others). It is known that with change in temperature, the

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strength of frozen dispersed rocks, such as sandstone, changes according to a regularity close to sqrt (abs T). For example, if the temperature increases from -6.0°C to -3.0°C, the compressive strength decreases by 1.4x. This exemplifies the importance of accounting for the temperature factor in design of structures in the permafrost area. The dependence of strength on moisture content is more complex and is significantly dependent on the temperature factor which determines the presence of unfrozen water [14, 15]. Along with the properties of the rocks, the depth of the active layer is an important factor in design of structures in the permafrost area and it determines which technical solutions are reliable [16, 17, 18]. The works [19-21] present the results of research surveying the influence of various initial parameters, including ice content, on the depth of the active layer, assuming that ice content is a constant that does not change along the coordinates [21].

The aim of the present work was to examine the influence of ice content variation along the vertical coordinate axis on the thawing depth and to assess the error in calculation of the thawing depth when the ice content is averaged along the depth of the active layer.

## 2 Methods

Suppose that the ice content in the soil changes linearly along the depth, that is, the following equations apply:

$$W(x) = a + bx \qquad W/_{x=0} = W_0 \qquad W/_{x=\delta} = W_к \tag{1}$$

$$W(x) = W_0 + (\text{grad } W) \cdot x \tag{2}$$

Where W is the ice content in the soil (unit fraction), $W_0$ is the ice content on the surface of the active layer (unit fraction), $W_k$ is the ice content at the depth of the thermal influence of the road (unit fraction), δ is the depth of the thermal influence of the road, m [22], x is the coordinate, m.

It is adopted that grad W is the ice content gradient along the depth of the thermal influence of the road area.

$$\text{grad } W = \tilde{g}; \qquad \tilde{g} = \frac{W_k - W_0}{\delta} \tag{3}$$

$$\tilde{g} = W(x)/_{x=s} = W_0 + \tilde{g} \cdot s \tag{4}$$

S is the thawing depth, m, $\tilde{g}$ is the ice content gradient along the depth of thermal influence area, °C/m.

The thawing depth of the soil can be found using the Stefan condition, which in this case has the form:

$$W(x)\frac{ds}{d\tau} = -\frac{\lambda}{\rho L}\frac{\partial T}{\partial x} \tag{5}$$

Where λ is the thermal conductivity coefficient of the thawed soil, W/mK, $\rho$ is the density of the frozen soil, kg/m$^3$, τ is time, s, T is temperature of the soil, °C.

Using the assumption about the linear profile of temperature change along the depth of the active layer of the soil at boundary conditions of the first kind, the solution is obtained in the following dimensionless form:

$$Fo = St[3S^2 + 2S^3\,(W - 1)]/6 \tag{6}$$

The following parameters are used in the expression:

$$\mathrm{Fo} = \frac{a\tau}{\delta^2};\ \mathrm{St} = \mathrm{LW_o}/\mathrm{C_p t};\ \mathrm{St''} = \mathrm{LW_k}/\mathrm{C_p t};\ \ \mathrm{S} = s/\delta;\ \mathrm{W} = \frac{\mathrm{W_k}}{\mathrm{W_o}}.$$

Here Fo is the Fourier criterion, St is the Stefan number (criterion), δ 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.

$$\mathrm{Fo} = \mathrm{S}^2\mathrm{St}/2 \qquad \text{or} \quad \mathrm{S} = \sqrt{2\mathrm{Fo}/\mathrm{St}} \tag{7}$$

It is apparent that the equation (7) is a specific case of the equation (6). It is relevant to assess the possibility of using the equation (7) in engineering calculations with an averaged ice content (ice content is considered constant) along the depth of the active layer of the soil. The error (as a percentage) that will result if the equation (6) is substituted for equation (7) can be found using the following expression:

$$\mathrm{e} = \mathrm{abs}[2\mathrm{S}(\mathrm{W} - 1)/3] \cdot 100\% \tag{8}$$

Correspondingly, the ratio between W and S which will not result in an error greater than 10%, the maximum permitted in engineering practice, is obtained using the equation:

$$\mathrm{W} = 1 - 0{,}15/\mathrm{S} \tag{9}$$

## 3 Results and Discussion

First of all, it needs to be noted that the error occurring during the calculation of the thawing depth when applying the assumption that ice content is constant along the depth of the active layer depends on W and S parameters and does not depend on the Fourier and Stefan criteria which determine the thawing depth of the soil. This applies because the error is relative and is measured as a percentage of the absolute value. In this case, in percentages of the thawing depth of the soil with the assumption that ice content is constant within the active layer of the soil.

To assess the influence of the ice content on thawing depth and examine the calculation error, variant calculations were done, and their results are presented as 2D and 3D charts in the figures 1-3. The figure 1 displays the dependence of the Fourier criterion (Fo) on the dimensionless thawing depth of the soil S at different ice contents of the active layer of the soil. The ice content values are indicated by the parameter W for two typical Stefan (St) number values. As the chart shows, for small thawing depths (shallower than 1.0 m), the unevenness of ice contents has almost no influence on the results both when the Stefan number equals 2 and when it is increased threefold. As the thawing depth increases to 2.0 m, the dependence of the Fourier number on the ice content is more significant and cannot be ignored either when the ice content increases (W > 1) or decreases (W < 1) with depth. At that, the higher the Stefan number, the greater the dependence.

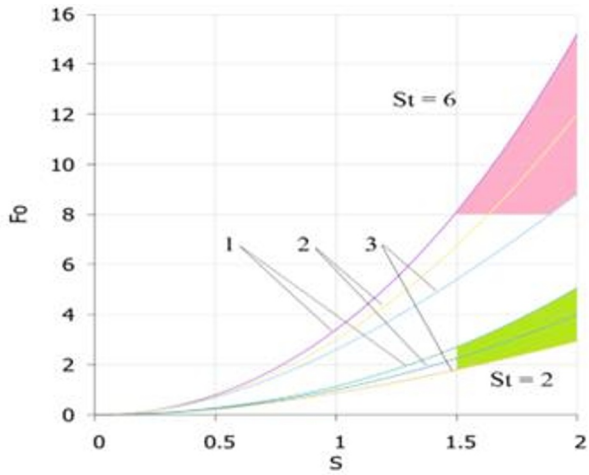


**Fig. 1.** Dependence of the Fourier criterion on the Stefan number at given dimensionless thawing depth of the sol for various values of the parameter W: 1 – 1.2, 2 – 1.0, 3 – 0.8.

The figure 2 shows as a 3D chart describing the degree of dependence of the dimensionless thawing depth on the Fourier and Stefan criteria at different degrees of ice content inequality.

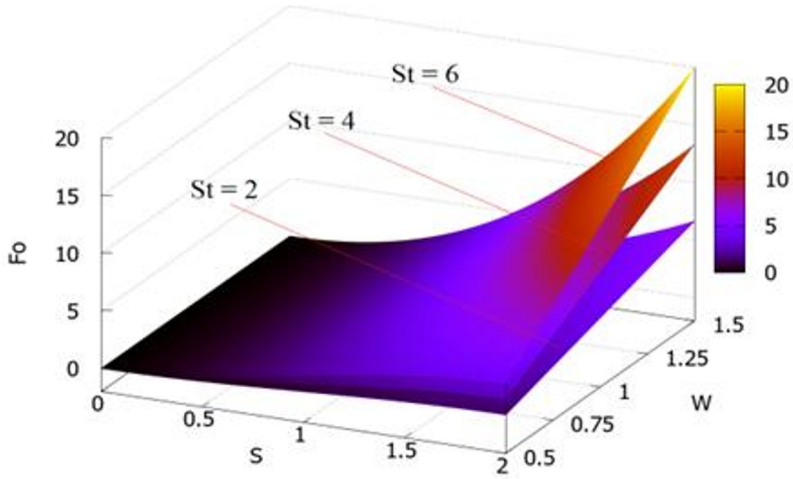


**Fig. 2.** Change in Fourier criterion depending on the parameter W and the dimensionless thawing depth of the soil at various Stefan number values.

An 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).

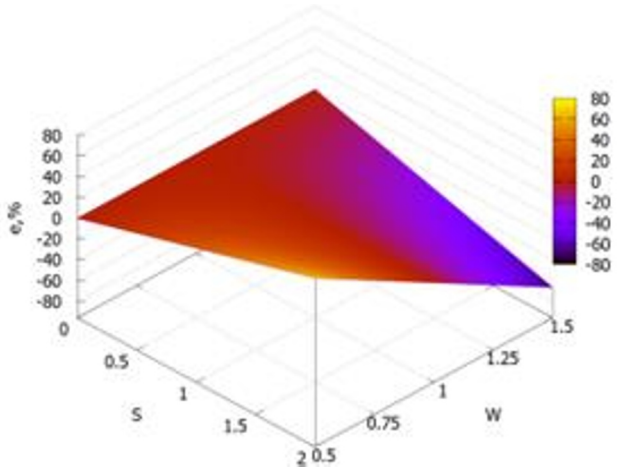


**Fig. 3.** The error in determination of the Fourier criterion, when not accounting for variation in ice content along the depth of the soil, for a given temperature for various values of the parameter W.

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.

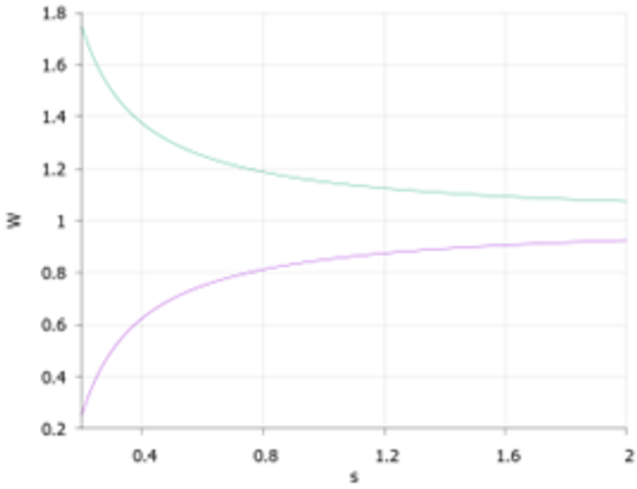


**Fig. 4.** The permissible ratio of the parameters S and W which secures that the error in determination of the Fourier criterion will be within permissible range.

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.

## References

1. Yu.V. Stanilovskaya, V.P. Merzlyakov, D.O. Sergeev, A.N. Khimenkov, Geoecology. Engineering Geology. Hydrogeology. Geocryology **4**, 367-378 (2014)
2. V.V. Shapran, Z.T. Fazilova, Transportation World (Mir Transporta) **18(2)**, 82-101 (2020)
3. S.E. Grechischev, L.V. Chistotinov, Yu.L. Shur, *Cryogenic Physical and Geological Processes and their Forecasting* (Nedra, Moscow, 1980)
4. S.I. Serikov, M.M. Shatz, Applied ecology. Urban development **4**, 162–171 (2018) DOI: 10.15593/2409-5125/2018.01.04
5. D.M. Shesternev, A.V. Litovko, Materials of reports of the XIV All-Russian Scientific and Practical Conference and Exhibition Prospects for the Development of Engineering Surveys in Construction in the Russian Federation, 309-314 (2018)
6. M.N. Zheleznyak, D.M. Shesternev, A.V. Litovko, Materials of reports of the XIV All-Russian Scientific and Practical Conference and Exhibition Prospects for the Development of Engineering Surveys in Construction in the Russian Federation, 223 – 227 (2018)
7. F. Niu, A. Li, J. Luo, et al., Cold Regions Science and Technology **133**, 7-14 (2017)
8. J. Gao, Q. Ma, R. Jingge, Arabian Journal of Geosciences **14(22)** (2021) DOI: 10.1007/s12517-021-08641-8
9. Q. Gao, Z. Wen, W. Feng, et al., Cold Regions Science and Technology **178**, 103-11. (2020)
10. M.V. Nikolaeva, G.P. Struchkova, Oil and Gas Technologies **4**, 56-60 (2018)
11. L.V. Eppelbaum, I.M. Kutasov, Polar Research **38**, 33-51 (2019) DOI: https://doi.org/10.33265/polar.v38.3351
12. J. Zhang, G. Qu, H. Jin, Cold Regions Science and Technology **3**, 243–247 (2010)
13. Xu. Guofang, Qi. Jilin, Wu. Wei, Springer Series in Geomechanics and Geoengineering, 227-236 (2019) DOI: https://doi.org/10.1007/978-3-319-89671-7_19

14. I.V. Votyakov, *Physical-Mechanical Properties of Frozen and Thawing Soils of Yakutia* (Nauka, Novosibirsk, 1975)
15. J. Teng, F. Shan, Z. He, et al., Experimental Study of Ice Accumulation in Unsaturated Clean Sand, 227-236 (2018) DOI: https://doi.org/10.1007/978-3-319-89671-7_19
16. A.F. Zhirkov, M.N. Zheleznyak, M.M. Shatz, M.A. Sitvtsev, Surveying and Mineral Development **5**, 22-32 (2021)
17. A.F. Galkin, Transportation Research Procedia **63**, 1224-1228 (2022) DOI: org/10.1016/j.trpro.2022.06.128
18. A.F. Galkin, V.Yu. Pankov, Journal of Applied Engineering Science **20(2)**, 395-399 (2022) DOI: 10.5937/jaes0-34379
19. A.F. Galkin, I.V. Kurta, Mining Information and Analytical Bulletin (scientific and technical journal) **2**, 82–91 (2020) DOI: 10.25018/0236-1493-2020-2-0-82-91
20. S.V. Kalinicheva, A.N. Fedorov, Geography and local history in Yakutia and adjacent territories of Siberia and the Far East, 40-44 (2022)
21. A.F. Galkin, V.Y. Pankov, Arctic and Antarctic **2**, 13-19 (2022) DOI: 10.7256/2453-8922.2022.2.38103
22. A.F. Galkin, Urbanism **4**, 1-9 (2022) DOI: 10.7256/2310-8673.2022.4.38879