

CALCULATIONS OF GROUND FREEZING DEPTH UNDER BARE AND COVERED WITH THE SNOW COVER GROUND SURFACE FOR THE SITE OF THE METEOROLOGICAL OBSERVATORY OF LOMONOSOV MOSCOW STATE UNIVERSITY FOR WINTER PERIODS OF 2011/12–2017/18*D.M. Frolov*

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Corresponding authors: D.M. Frolov, denisfrolov@mail.ru**Citation:** Frolov DM, 2019. Calculation of ground freezing depth under bare and covered with the snow cover ground surface on the site of the meteorological observatory of Lomonosov Moscow State University for winter seasons of 2011/12–2017/18. *Environmental dynamics and global climate change*. 10:86–90. https://doi.org/10.17816/edgcc21203

The calculating scheme for estimation of ground freezing depth under bare and covered with the snow cover ground surface on basis of air temperature and snow cover thickness is constructed and the example of calculations is performed for the site of the meteorological observatory of Lomonosov Moscow State University for winter periods of 2011/12–2017/18. The comparison of results of estimation scheme and observations indicated good correspondence.

Key words: Snow cover, ground freezing, air temperature

Построена расчетная схема для определения глубины промерзания под оголенной и покрытой снегом поверхностью на основе данных о температуре воздуха и толщине снежного покрова и произведен пример расчета для площадки метеообсерватории МГУ за зимние периоды 2011/12–2017/18. При сопоставлении результатов расчетов и измерений на площадке метеорологической обсерватории МГУ получено хорошее соответствие.

Ключевые слова: Снежный покров, промерзание грунта, температура воздуха.**INTRODUCTION**

Thermal regime of winter periods and peculiarities of snow accumulation mostly determine the thermal regime of underlying grounds and its freezing depth. According to the known data on long-term averaged regime of snow accumulation and seasonal variations of air temperature for the particular region and on the base of construction norms the depth of freezing and placement of underground pipelines are determined. However variations in the process of intraseasonal snow-fall deposition, accumulation of snow cover and seasonal variations of air temperature in relation to mean values lead to variations of ground temperature, variations of ground freezing depth and hazards for underground pipelines. Also variations of absolute values and the dynamics on the ground freezing depth are important for development of microbiota and root systems of plants. And more over, as known, accumulation of snow cover may lead to thawing of permanently frozen ground, increase of seasonal thawed layer and disappearance of permafrost, but the absence of snow cover

may lead to occurrence of permafrost in the zones of its sporadic presence or absence.

That is why V.A. Kudriavcev [Kudriavcev, 1954] characterized warming and cooling action of snow cover on the ground depending on regime of snow accumulation and on its duration and suggested an equation for estimation of ground freezing depth including snow cover thickness, its thermal properties and amplitude of yearly air temperature oscillations. In the works of A.V. Pavlov [Pavlov, 1966] snow cover on the ground surface is considered as additional layer with thermal resistance and this is used in the formula for ground freezing depth calculations. Modern continuation of these works one can find in the dissertation of E.E. Machulskaya [Machulskaya, 2001] and also in the works of foreign authors [DeGaetano et al., 2001, Jafarov et al., 2012].

PROBLEM SETTING

For estimation of role of snow cover in ground freezing depth variations the calculations of ground freezing depth on basis of air temperature and snow

cover thickness under bare and covered with the snow cover ground surface is performed for the site of the meteorological observatory of Lomonosov Moscow State University for winter periods of 2011/12–2017/18. The description of soil and microclimatic conditions and analysis of ground freezing depth measurements under bare and covered with the snow cover ground surface for the site of the meteorological observatory of Lomonosov Moscow State University with cryopedometers of Danilin and Ratomskii for 1955–2013 are presented in the work of [Korneva, Lokoshchenko, 2015]. In this work the calculations of ground freezing depth and the comparison of results of calculation scheme and observations [Environmental and climate..., 2012–2019] are presented. The estimation of difference of air temperature and covered with snow soil surface for the territory of Eurasia is given in general in the work of [Sherstiukov, Anisimov, 2018].

The calculating scheme for ground freezing for the case of bare ground is constructed on basis of two layer media heat conductivity problem (frozen and thawed ground) with phase transition on the boundary of frozen and unfrozen ground. For the case of covered with snow ground the calculating scheme is constructed on basis of three layer media heat conductivity problem (snow cover, frozen and thawed ground) also with the phase transition on the boundary of frozen and unfrozen ground. Heat balance equation includes phase transition energy, inflow of heat from unfrozen ground and outflow to frozen ground, snow cover and atmosphere. The heat flux is calculated on basis of Fourier law as a product of heat conductivity and temperature gradient. It is supposed, that temperature changes in each media linearly like in [DeGaetano et al., 2001]. For snow cover and frozen ground the formula of heat conductivity of two layer media is used.

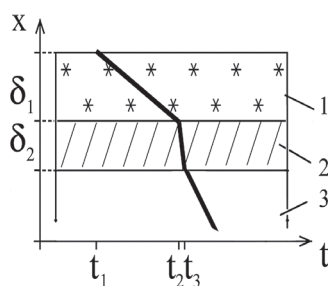


Fig. 1. Temperature distribution in the media, consisting of snow cover (1), layer of frozen (2) and thawed ground (3)

Рис. 1. Распределение температуры в среде, состоящей из снежной толщи (1), слоя мерзлого (2) и слоя талого грунта (3)

MATHEMATICAL MODELING

The calculations of ground freezing depth under bare and covered with snow cover ground in winter period on basis of daily data on air temperature (and snow thickness and heat conductivity of snow cover) allows estimating the rate of movement of ground freezing interface during this winter period. The rate of movement of ground freezing interface can be expressed as

$$F_1 = cLV + F_2 \quad \text{or}$$

$$dh_{fg}/d\tau = V = (F_1 - F_2)/cL, \quad \text{where}$$

F_1 — is heat outflow through frozen ground (and snow cover) from ground freezing interface (W/m^2) into atmosphere;

$cLV = cLdh_{fg}/d\tau$ — heat value for phase transition in the ground, c — ground moisture content ($1\text{--}4 \text{ kg}/\text{cm}^3\cdot\text{m}^2$), (last value correspond to full filling of porous by water for light clay with density $2000 \text{ kg}/\text{m}^3$ and porosity coefficient 0.617 [Trofimov, 2005] and was used in calculations);

L — energy of H_2O phase transition ($335 \text{ kJ}/\text{kg}$),

$V = dh_{fg}/d\tau$ — rate of movement of ground freezing interface (cm/s);

F_2 — heat outflow for cooling of thawed ground in front of ground freezing interface (W/m^2).

Heat flux is expressed according to Fourier law by means of temperature gradient and heat conductivity as $F = -\lambda (\text{grad } T)$. In the case of bare ground surface it can be expressed like:

$$F_1 = -\lambda \frac{\Delta T}{\Delta x} = \lambda_{fg} \frac{-T_{air}}{h_{fg}}.$$

In the case of presence of snow cover the heat conductivity and heat flux through combination of two media (snow and frozen ground) according to [Mikheev, 1977] can be expressed as:

$$F_1 = -\lambda \frac{\Delta T}{\Delta x} = \frac{-\Delta T}{\left(\frac{\Delta x_s}{\lambda_s} + \frac{\Delta x_{fg}}{\lambda_{fg}}\right)} = \frac{-T_{air}}{\left(\frac{h_s}{\lambda_s} + \frac{h_{fg}}{\lambda_{fg}}\right)}.$$

Here T_{air} — air temperature, h_s и h_{fg} — snow cover thickness and ground freezing depth, and λ_s and λ_{fg} — heat conductivity of snow and frozen ground and this expression valid also for $h_s = 0$.

It was supposed, that on the depth of 10 m in ground there is a point of zero annual temperature oscillation with temperature value T_0 about 7°C (correspond to annually averaged temperature in Moscow now). That is why

$$F_2 = -\lambda_{thg} \frac{\Delta T}{\Delta x} = \lambda_{thg} \frac{T_0}{10 - h_{fg}}.$$

Here λ_{thg} — heat conductivity of thawed ground. According to [Trofimov, 2005] averaged heat conductivity of the thawed and frozen ground λ_{thg} and

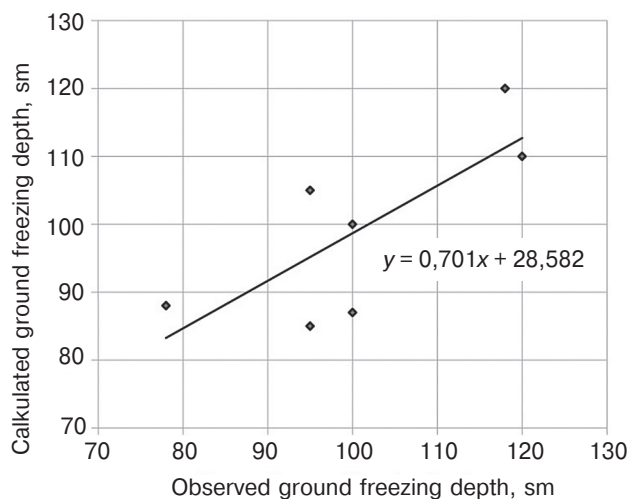


Fig. 2. Maximal ground freezing depth under bare site surface of the meteorological observatory of Lomonosov Moscow State University for the winter periods of 2011/12-2017/18 (comparison of observed and calculated data and trend line $y = 0,7x + 28,6$)

Рис. 2. Расчетная и измеренная максимальная глубина промерзания под открытой поверхностью для площадки метеообсерватории МГУ за зимние периоды 2011/12–2017/18

λ_{fg} — was assumed to be equal 1.4 and 1.8 W/m °C correspondingly. Averaged heat conductivity of snow λ_s according to the [Pavlov, 1979] was assumed to be equal 0.18 W/m °C.

The differential scheme $h_{fg}(t_{n+1}) = h_{fg}(t_n) + \Delta t V(t_n)$ was constructed by Euler approximation for the equation for the rate of ground freezing depth. By obtained differential scheme the

calculations of ground freezing depth were done for the winter seasons of 2011/12-2017/18 and the comparison of obtained results with the observed data for bare and covered with snow site surface of the meteorological observatory of Lomonosov Moscow State University was performed. And this way the calculations were done with the step-size of one day. For initial conditions, it was supposed that frozen ground thickness h_{fg} was equal 0.5 cm. For each time step (for each day) the rate of movement of freezing interface V and the value frozen ground thickness h_{fg} for the next day (time-step) were calculated.

The results of calculations and discussion

The results of calculations of maximal ground freezing depth for the bare site surface of the meteorological observatory of Lomonosov Moscow State University for the winter periods of 2011/12-2017/18 and theirs comparison with the observed data are displayed on the Fig. 1 and in table 1 and indicate general consistency.

From the table 1 one can see, that averaged difference of calculated and observed maximal ground freezing depth under bare site surface of the meteorological observatory of Lomonosov Moscow State University for the winter periods of 2011/12-2017/18 is 1.6 cm and under the covered with snow site surface it is 4 cm. But the main advantage of the calculating scheme is that it reproduce the dynamic of the ground freezing process well, so the example of results of calculations for ground freezing depth under bare and covered with snow site surface of the meteorological observatory of

Table 1 / Таблица 1

Comparison of calculated and observed maximal ground freezing depth under bare and covered with snow site surface of the meteorological observatory of Lomonosov Moscow State University for the winter periods of 2011/12-2017/18.

Сопоставление расчетной и измеренной максимальной глубины промерзания под оголенной поверхностью и поверхностью с естественным покровом для площадки метеообсерватории МГУ за зимние периоды 2011/12-2017/18.

Winter period	Maximal ground freezing depth under bare site surface, cm		Maximal ground freezing depth for the covered with snow site surface, cm	
	observed	calculated	observed	calculated
2011/12	120	110	18	10
2012/13	118	120	8	12
2013/14	100	87	18	4
2014/15	95	85	30	7
2015/16	78	88	25	30
2016/17	100	100	3	7
2017/18	95	105	14	18
Max diff.	13		23	
Min diff.	-10		-5	
Aver. diff.	1,6		4	

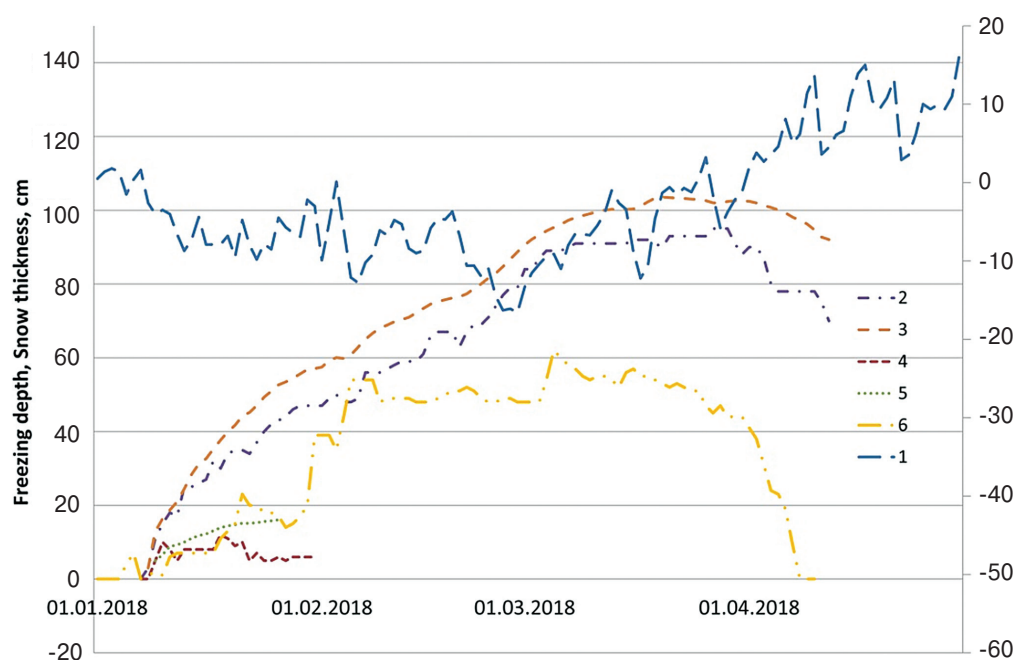


Fig. 3. Variations of air temperature and ground freezing depth according to the data of calculations and observation under bare and covered with snow site surface of the meteorological observatory of Lomonosov Moscow State University for the winter period 2017/18 (the results of calculations for ground freezing depth for the bare (3) and covered with snow site surface (5) and theirs comparison with the observed data (2 and 4 correspondingly). Air temperature (1) and snow cover thickness (6))

Рис. 3. Изменения температуры воздуха и глубины промерзания по данным расчетов и наблюдений для открытой и покрытой снегом поверхности грунта для метеостанции МГУ для зимнего периода 2017/18 (1 — температура воздуха, 2 — наблюдаемая и 3 — расчетная глубина промерзания под открытой поверхностью, 4 — наблюдаемая и 5 — расчетная глубина промерзания под естественным покровом, 6 — толщина снежного покрова)

Lomonosov Moscow State University for the winter period 2017/18 and theirs comparison with the observed data is displayed on the Fig. 3.

CONCLUSION

Considered in this work method of linear gradients differs from considered before in the classical book of A.N. Tikhonov and A.A. Samarskii [Tikhonov and Samarskii, 1999] (first edition from 1951) or in the works of A.V. Pavlov [Pavlov, 1966] or presented in the other works method, where for calculation of seasonal dynamics of ground freezing depth the heat conductivity partial differential equation of second order for space and first order for time is used. In this work there is only reduced ordinary differential equation of first order for time is used. Solving of this reduced first order ODE is simpler and could be done within Excel program.

Generally, the averaged ground freezing depth in Moscow region according to the long-term data of the observation network (<http://ecomos.ru/kadr22/nowostBlank.asp?fajl=new21.10.09.htm>) reaches 85 cm at normal air temperature and snow cover accumulation regime. Smaller ground freezing depth on the site of the meteorological observa-

tory of Lomonosov Moscow State University can be explained by presence of soil heating by pipelining in the vicinity of the site [Environmental and climate..., 2012] and heating effect of town heat island. Obtained non consistency of calculated and observed data can also be explained that in heat balance equation the ground cooling (heating) term was omitted but only phase transition was considered. Also the variation of moisture content in the ground was neglected.

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