Influence of Intra-seasonal Snowfall Deposition, the Peculiarities of Snow Cover Accumulation and Winter Season Temperature Variation on Ground Freezing Depth

Denis Frolov

Abstract On basis of the data of winter seasons on snowfalls, thermal regime and peculiarities of snow accumulation regime and according to the calculating scheme with three-layer media heat conductivity problem (snow cover, frozen and thawed ground) and with phase transition on the boundary of frozen and unfrozen ground with daily resolution the estimation of ground freezing depth for the North-East part of European territory of Russia for the period of 1988–2008 was conducted. The Heat balance equation included phase transition energy, inflow of heat from unfrozen ground and outflow to frozen ground, snow cover and atmosphere. The heat flux was calculated on basis of Fourier law as a product of heat conductivity and temperature gradient. The assumption that snow cover consists of different layers deposited by different snowfalls and having different structure and density and heat conductivity depending on its density was taken. The density and heat conductivity of each layer and the whole thickness of snow cover were determined and the regional stratigraphic column for snow cover was compiled and the calculation of ground freezing intensity and freezing depth was conducted. The comparison of estimated with calculating scheme and observed values of ground freezing depth were performed and the correlation of equal 0.76–0.77 of them was stated.

Keywords Snowfalls · Snow accumulation regime · Winter air temperature · Ground freezing depth

1 Introduction

Thermal regime of winter season and peculiarities of snow accumulation are important factors for ground temperature and freezing depth. According to the data on these processes and on basis of construction norms the depth of freezing and placement of underground pipelines are determined. However, variations in the process of intra-seasonal snowfall deposition, accumulation of snow cover and seasonal variations of

D. Frolov (✉)
Geographical Faculty, Lomonosov Moscow State University, Moscow 119991, Russia
e-mail: denisfrolovm@mail.ru

A. Petriaev and A. Konon (eds.), *Transportation Soil Engineering in Cold Regions, Volume 1*, Lecture Notes in Civil Engineering 49,
https://doi.org/10.1007/978-981-15-0450-1_1

air temperature in relation to mean values lead to variations of ground temperature, variations of ground freezing depth and hazards for underground pipelines. Kudriavcev [1] characterized warming and cooling action of snow cover on the ground depending on snow accumulation regime 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 work of Park et al. [2] by means of experiments with ground surface model CHANGE was established, that intensive snowfalls at the beginning of winter season make thermos-isolating snow cover before coming of frost and prevent ground cooling and reduce freezing or increase thawing depth.

In the rock ground freezing modelling, Haberkorn et al. [3] the model Alpine3D consisting of the 3D atmospheric processes model coupled with the 1D energy balance model SNOWPACK is used.

In our case calculating scheme for ground freezing was constructed on basis of three-layer media heat conductivity problem (snow cover, frozen and thawed ground) with phase transition on the boundary of frozen and unfrozen ground. Heat balance equation included phase transition energy, inflow of heat from unfrozen ground and outflow to frozen ground, snow cover and atmosphere. The heat flux was calculated on basis of Fourier law as a product of heat conductivity and temperature gradient. It was supposed, that temperature changes in each media linearly. For snow cover and frozen and thawed ground the experimentally verified in refrigerated chamber formula of heat conductivity of three-layer media was used.

Inconsistency of prediction of ground freezing depth obtained on basis of estimation scheme with the observed ones (possibly in two times) makes it possible to conclude that important role also played the assumption of continuity and uniformity of heat-conducting media properties (of snow cover) and that for snow cover it was assumed the seasonal mean values of density and heat conductivity. Also important role plays relation snow cover heat conductivity on its density, structure and texture. In reality snow cover is not a continuous and uniform media but consists of layers with different structure and density. Consideration of meteorological data of air temperature, precipitation and snow thickness and snowfall intensity on the nearest meteorological station makes it possible to defined density and heat conductivity of snow cover and compile the regional stratigraphic column for snow cover and to conduct the calculation of ground freezing intensity and freezing depth more precisely.

2 Materials and Methods

On basis of meteorological data on air temperature, precipitation and snow cover thickness extracted data on deposition and intensity of snowfalls at the nearest meteorological station Narayan-Mar [4] (see distribution on Fig. 1a). Generalized stratigraphy columns are compiled for this region for winter seasons 1990/91–2015/16 like in [5, 6] (see Fig. 1b). On the basis of relation of snow heat conductivity on density

denisfrolovm@mail.ru

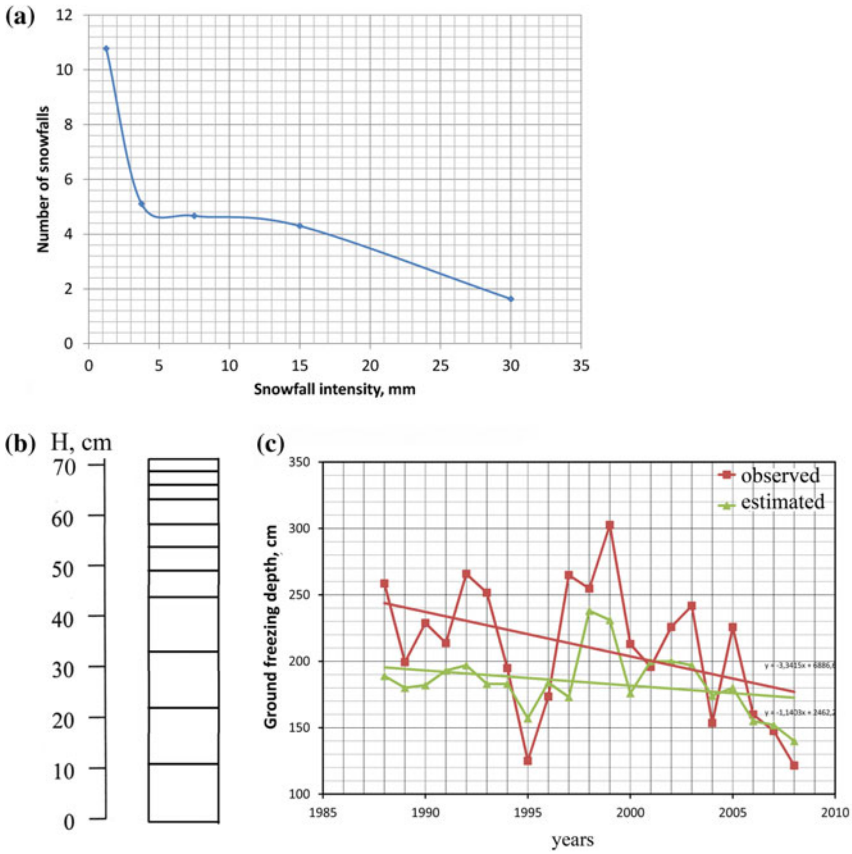

Fig. 1 **a** Average number of snowfalls of particular intensity according to data of meteorological station Narayan-Mar for 1988–2008, **b** generalized stratigraphic column of snow cover for meteorological station Narayan-Mar for 1988–2008, **c** variations of winter season observed and estimated ground freezing depth for meteorological station Narayan-Mar in 1988–2008

according to Pavlov [7] formula the estimation of heat conductivity of separate snow layers was conducted. According to formula of heat conductivity of multilayer media

$$\frac{\lambda}{\Delta x} = \frac{1}{\frac{\Delta x_1}{\lambda_1} + \cdots + \frac{\Delta x_n}{\lambda_n}} \tag{1}$$

And on basis of information on snow layers, the ground freezing depth was calculated.

The calculations of freezing of the covered by the snow cover ground in winter period on basis of daily data on air temperature and snow thickness and heat conductivity of snow cover allow estimating the rate of movement of ground freezing interface during this winter period. The rate of movement of ground freezing interface can be expressed with the formulas.

The equation of heat balance can be written as:

$$F_1 = cLV + F_2, \tag{2}$$

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

cLV heat value for phase transition in the ground, c—ground moisture content (1–4 kg/cm*m^2), (last value correspond to full filling of porous by water for light clay with density 2000 kg/m^3 and porosity coefficient 0.617 [8]), L—energy of H_2O phase transition (335 kJ/kg), V—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 $F = \lambda\,(\mathrm{grad}\,T)$. Heat conductivity and heat flux through combination of two media (snow and frozen ground) according to [9] can be expressed as:

$$F_1 = \lambda \frac{\Delta T}{\Delta x} = \frac{\Delta T}{\left(\frac{\Delta x_s}{\lambda_s} + \frac{\Delta x_{fg}}{\lambda_{fg}}\right)} = \frac{T_{air}}{\left(\frac{h_s}{\lambda_s} + \frac{l_{fg}}{\lambda_{fg}}\right)} \tag{3}$$

here

T_{air} air temperature,
h_s and l_{fg} snow cover thickness and ground freezing depth, and
λ_s and λ_{fg} heat conductivity of snow and frozen ground.

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 3 °C. That is why

$$F_2 = \lambda_{thg} \frac{\Delta T}{\Delta x} = \lambda_{thg} \frac{T_0}{10 - l_{fg}} \tag{4}$$

Here λ_{thg} is heat conductivity of thawed ground.

For validation of three-layers-calculating-scheme the experiment of one direction freezing of covered with snow sand sample was conducted in refrigerated chamber under the action of negative temperatures. The intensity of freezing and rate of movement of phase transition front were determined and compared with obtained by calculating scheme values. For this reason, the dry sand sample with the mass of 5.2 kg, 1.35 g/cm^3 density and less than millimeter grain size was placed in plastic volume of 14 * 14 * 30 cm. One liter of distilled water was also added into the sand in order to become its' moisture content maximal and equal to 20%. The volume with wet sand was placed into heat isolating cover for one direction freezing and thermal probes on the levels −20, −10 and 0 cm from the upper sand surface level were also placed. The installation was placed in the refrigerated chamber with negative temperature of −5 °C. As upper sand surface was cooled down, the coarse-grained snow with initial density of 0.3 g/cm^3 was placed on the top of sand and thermal probe on the level +5 cm from the upper sand surface was placed close to the upper outer snow surface.

In a while of cooling of the installation the phase transition on the lower snow–upper ground surface happened. Further at assumed heat losses of sample at one direction freezing (1 J/s) the calculated time of freezing of the whole ground sample was 90 h. In reality, the phase transition in the ground sample finished in 84 h. This could be explained by not accounted heat losses through the sidewalls of the installation. Therefore, the three-layers-calculating-scheme estimations were validated with experimental observations.

3 Results

Calculations of the ground freezing depth were done according to the constructed calculating scheme on basis of heat conductivity Stephan problem with multilayer heat conductivity. For this reason on basis of knowledge about winter snowfalls' frequency and intensity the generalized snow stratigraphy column for each winter season were compiled and the heat conductivity of the multilayer system was determined.

Calculations were done with the step-size of one day. For initial conditions, it was supposed that frozen ground thickness l_{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 l_{fg} for the next day (time step) were calculated.

According to [8] averaged heat conductivity of thawed and frozen ground was assumed to be equal to 1.4 and 1.8 W/m °C correspondingly.

The results of calculations by described estimation scheme determined general consistency of calculated ground freezing depth values with the observed ones (see Fig. 1c). The correlation coefficient is equal to 0.76–0.77, which is quite good for such simple calculation scheme.

The work is done in a frame of state topic AAAA-A16-116032810093-2 «Mapping, modelling and assessment of risk of hazardous natural processes».

References

1. Kudryavtsev VA (1954) Temperature of the upper horizons of permafrost thickness within the USSR. Akad. Nauk SSSR, Leningrad
2. Park H, Fedorov AN, Zheleznyak MN, Konstantinov PY, Walsh JE (2014) Effect of snow cover on pan-Arctic permafrost thermal regimes. Clim Dyn 9–10(44):2873–2895

3. Haberkorn A, Wever N, Hoelzle M, Phillips M, Kenner R, Bavay M, Lehning M (2016) Distributed snow and rock temperature modelling in steep rock walls using Alpine3D. Cryosphere Discuss. https://doi.org/10.5194/tc-2016-73
4. Specialized data for climatic research. http://aisori.meteo.ru/ClimateR
5. Golubev VN, Petrushina MN, Frolov DM (2017) Snowfall events as a factor of snow cover's stratigraphy formation. In: Lupo A (eds) The 2nd international electronic conference on atmospheric sciences, vol 2 (2017)
6. Golubev VN, Petrushina MN, Frolov DM (2008) Winter regime of temperature and precipitation as a factor of snow-cover distribution and its stratigraphy. Ann Glaciol 49:179–186
7. Pavlov AV (2008) Cryolithozone monitoring. Academician Publishing House, Novosibirsk
8. Trofimov VT (2005) Soil science. MSU Publishing, Moscow
9. Mikheev MA, Mikheeva I (1977) Fundamentals of heat transfer. Energiya, Moscow