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Calculation scheme of ground freezing depth in Terskol

Abstract. During the construction of avalanche-retaining geotechnical structures in mountainous areas comes up the problem of fixing and stability of these structures in conditions of seasonal and/or long-term freezing of the ground. This paper evaluates the influence of snow cover and air temperature on the depth of freezing and soil stability based on the developed calculation scheme for the winter seasons 2015/16-2019/20 in the Elbrus region. The calculation scheme was based on the problem of thermal conductivity of a three-layer medium (snow, frozen, and thawed soil) with a phase transition at the boundary. The heat balance equation included the energy of the phase transition, the inflow of heat from the thawed ground and the outflow to the frozen ground, and, in the presence of snow cover, through it to the atmosphere.

Keywords: calculating scheme; air temperature; snow cover; ground freezing; mountain regions; construction stability

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Introduction

One of the factors of soil stability on slopes during the construction of avalanche-retaining geotechnical structures in mountainous areas is the freezing of the underlying soil since in mountainous areas the soil can be frozen for eight or more months. However, the recent changes in air temperature and precipitation (primarily in the form of snow) [**5**] lead to a change in the depth and duration of freezing of the soil and, as a result, a decrease in its stability. A model study of soil freezing in the mountains was carried out in [**6**]. In this paper, based on the developed calculation scheme, the depth of ground freezing for the last five winter seasons is estimated based on data on the thickness of snow cover and air temperature for the weather station Terskol. Weather Station Terskol is located in the valley Azau in Elbrus region at an altitude of 2141 m above sea level. The average temperature in January is -7°C, July - 13.4°C, and the average sum of negative monthly temperatures in the winter period (November-March) is -20°C. During the period of snow accumulation (in November-March), an average of about 280 mm of precipitation falls, causing the accumulation of snow cover up to 70-80 cm thick. Calculations of changes in the depth of ground freezing were performed according to the proposed calculation scheme based on data on the thickness of snow cover and air temperature based on a three-layer model of the medium (thawed soil, frozen soil, snow) and assuming a linear change in temperature in the media and heat flow according to Fourier's law. This simplified calculating scheme is used since it requires only air temperature and snow thickness data and is very easy in conducting calculations using the solution of only one ordinary differential equation at each time step.

Methodology

The article calculates the freezing depth based on data on air temperature and snow cover thickness for weather stations Terskol for the snow-covered soil surface for the winter seasons 2015/16-2019/20 according to the proposed calculation scheme. The calculation scheme was based on the problem of thermal conductivity of a three-layer medium (snow, frozen and thawed soil) with a phase transition at the boundary of frozen and thawed soil. The heat balance equation included the energy of the phase transition, the inflow of heat from the thawed ground and the outflow to the frozen ground and, in the presence of snow cover, through it to the atmosphere. The heat flux was calculated according to Fourier's law, as the product of the thermal conductivity and the temperature gradient. It was assumed that the temperature in each medium varies linearly (for example, [3]). For snow cover and frozen ground, the formula of thermal conductivity of a two-layer medium was used.

The calculation of ground freezing based on data on air temperature and snow cover thickness and thermal conductivity during the winter period made it possible to estimate the intensity of the freezing front movement during this time period. The dependence of the speed of the freezing front movement was found according to the calculated scheme. The scheme took into account the freezing of the ground from below on the frozen ground mass in winter, based on data on the daily air temperature (and the thickness and thermal conductivity of the snow cover).

The heat balance equation was written as $F_1=cLV+F_2$, or as:

$$dh_{fg} /dt =V= (F_1 -F_2)/cL, \quad (1)$$

where: F_1 – heat outflow through the frozen ground (and snow cover) from the freezing front (W/m^2) to the atmosphere; $c\ L\ V = c\ L\ dh_{fg}\ /d\tau$– consumption heat at the phase transition, c, moisture content of the soil (1-4 kg/cm*m^2), (last value corresponds to the complete filling of pores with water from a lightweight clay with a density of 2000 kg/m^3 and a porosity 0,617 [1]); L – energy of the phase transition (335 kJ/kg); $V = dh_{fg}\ /d\tau$ – the speed of the freezing front (cm/s); F_2 – heat exchange in the cooling melt the ground before the freezing front (W/m^2).

The heat flux was expressed according to the Fourier law: $F= -\lambda$ grad T. The heat flow through the frozen ground from the freezing front to the atmosphere in the case of snow cover was expressed in terms of thermal conductivity and heat flow of a combination of two media (snow cover and frozen ground) how to:

$$F_1 = -\lambda \frac{\Delta T}{\Delta x} = -\frac{\Delta T}{\frac{\Delta x_s}{\lambda_s} + \frac{\Delta x_{fg}}{\lambda_{fg}}} = \frac{-T_{air}}{\frac{h_s}{\lambda_s} + \frac{h_{fg}}{\lambda_{fg}}}, \quad (2)$$

Here T_{air} is the air temperature, h_s and h_{fg} are the snow thickness and freezing depth, and λ_s and λ_{fg} are the thermal conductivity of snow and frozen ground.

It was assumed that at a depth of 10 m in the ground there is a point of zero annual temperature fluctuations T_0 with an average annual value of about 7°C. Therefore

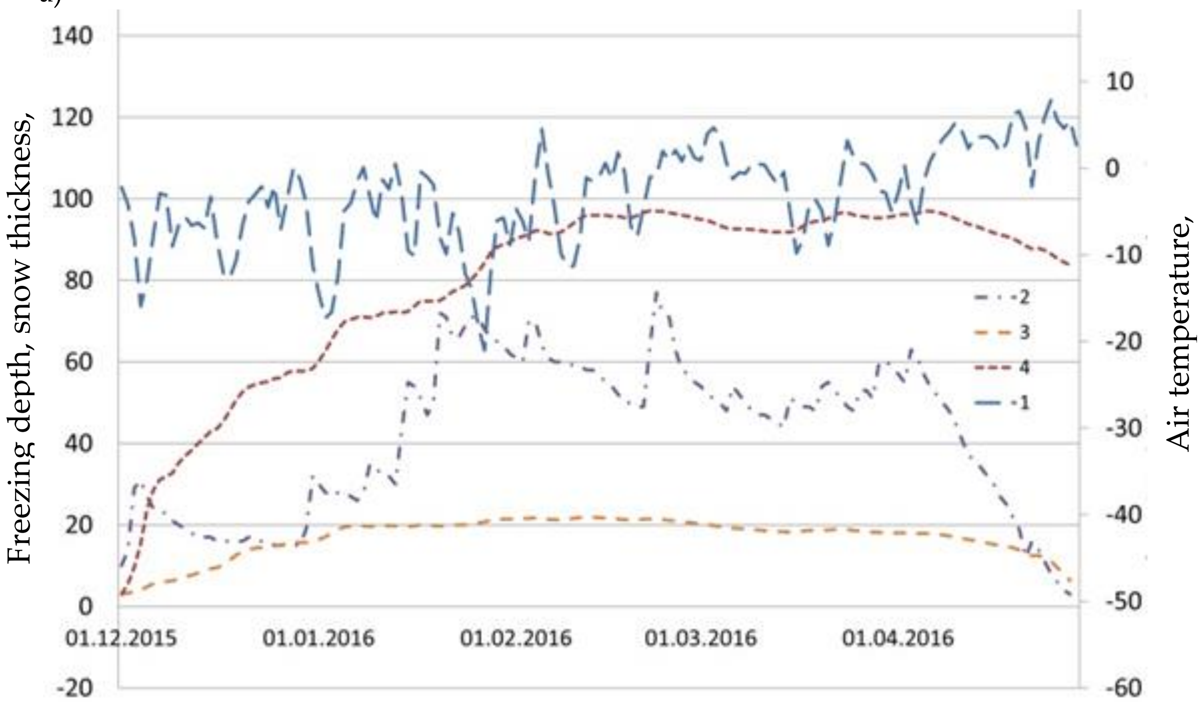
$$F_2 = -\lambda_{thg} \frac{\Delta T}{\Delta x} = \lambda_{thg} \frac{T_0}{10 - h_{thg}}, \quad (3)$$

Here λ_{thg} is the thermal conductivity of thawed soil. Calculations were performed in one-day increments. At first, it was assumed that the thickness of the frozen groundh_{fg} was 0.5 cm. At each time step (every day) was calculated (calculated) the freezing rate V and the value of the frozen ground thicknessh_{fg} for the next day (time step). According to [1], the average thermal conductivity of thawed and frozen clay soil could be taken as 1.4 and 1.8 W/m°C. The average thermal conductivity *of* snow λ_c was calculated relative to the density according to the formula of A. V. Pavlov [**2**] and was taken equal to 0.18 W/m°C.

Results and Discussion

In this paper, a difference scheme was constructed for the derived first-order time differential equation for changing the depth of soil freezing by approximating this differential equation by the explicit Euler method:$h_{fg}(t_{n+1}) =h_{fg}(t_n)+ \Delta T\ V(t_n)$. According to the obtained difference scheme, for each winter season 2015/16-2019/20, calculations of changes in the depth of soil freezing were made. An example of the calculation results for the winter season 2016/17 is shown in figure 1.

a)


Freezing depth, snow thickness,
Air temperature,
140
120
100
80
60
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20
0
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01.12.2015
01.01.2016
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-2
3
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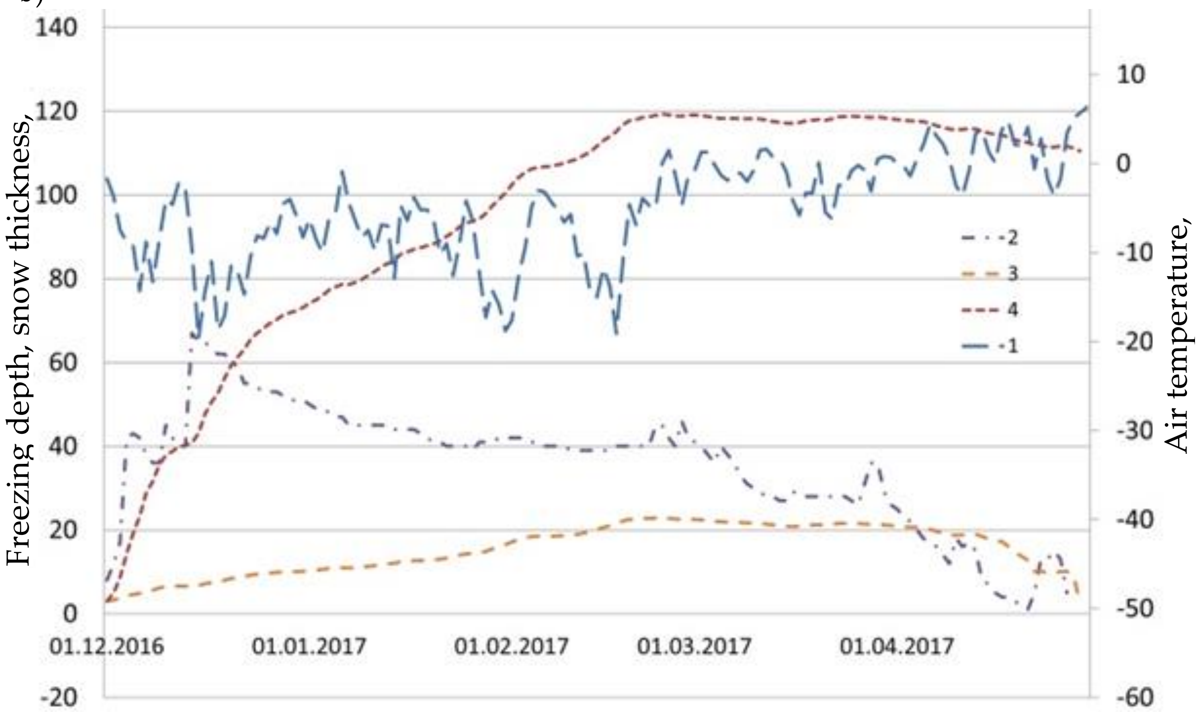
-1

b)


Freezing depth, snow thickness,
Air temperature,
140
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01.12.2016
01.01.2017
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01.04.2017
-2
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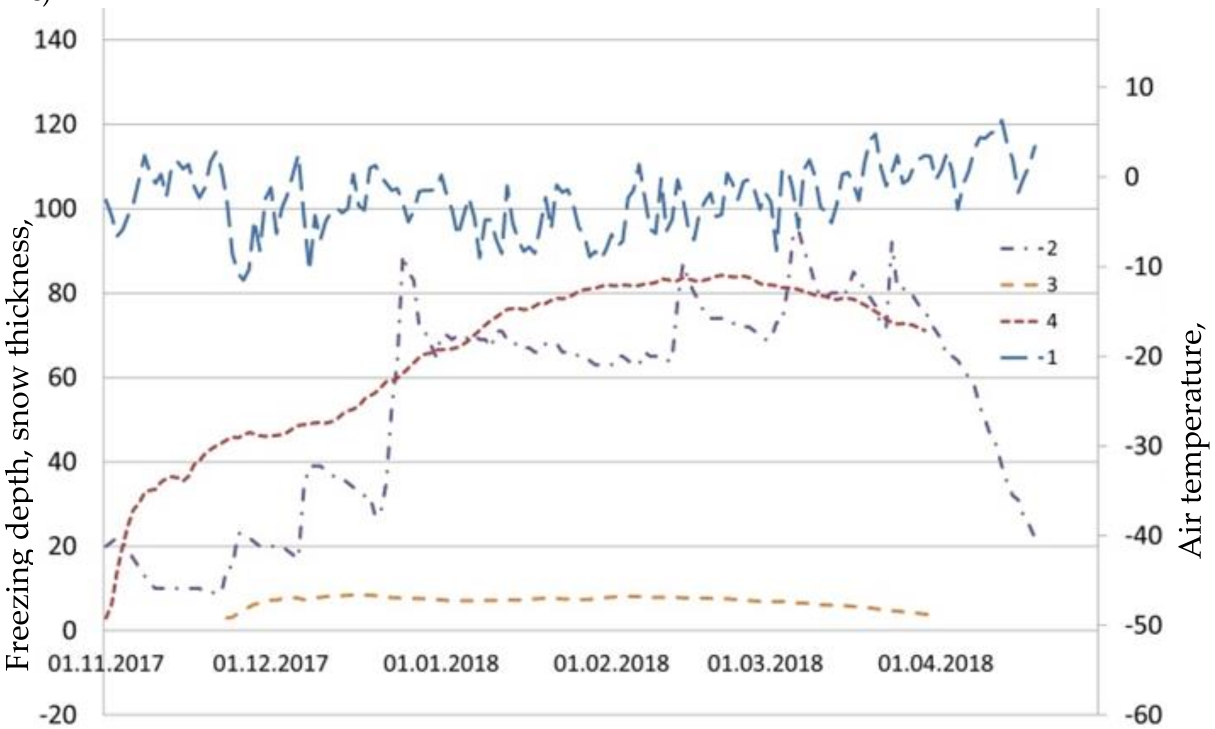
4
-1

c)



d)

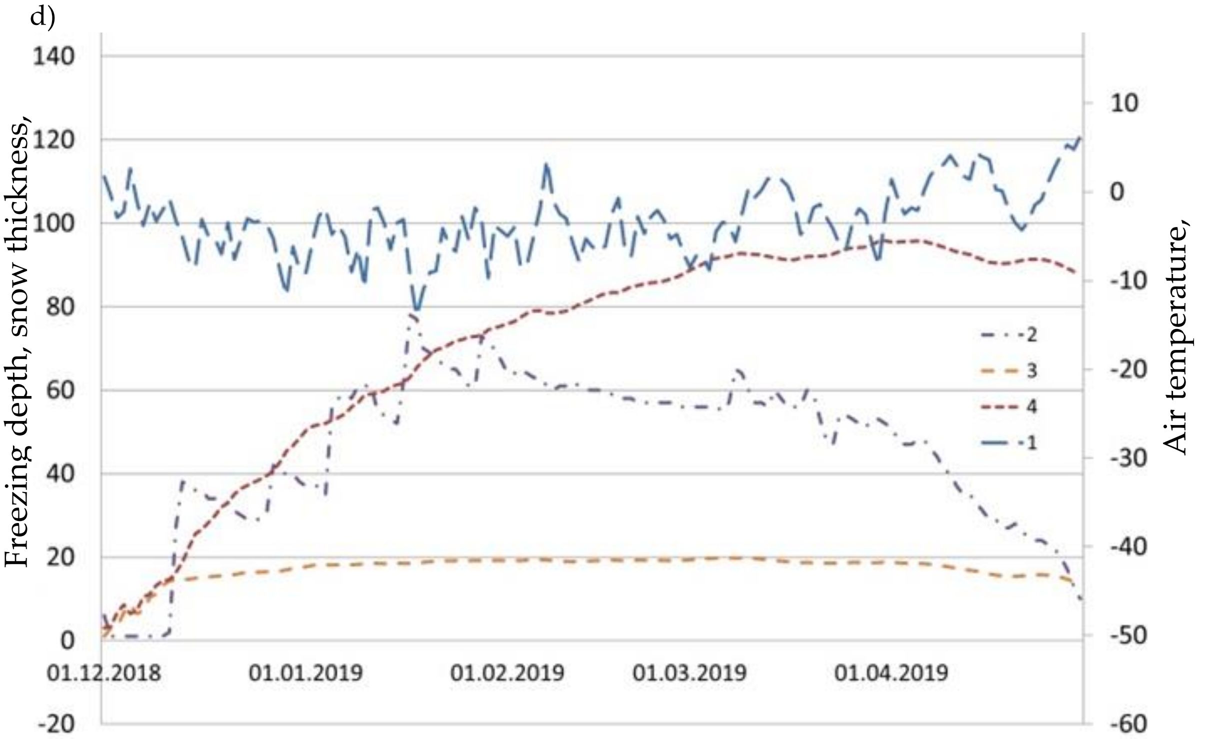


Figure 1. Changes in air temperature and freezing depth based on calculations for snow-covered and exposed ground surfaces for a weather station Terskol for winter periods 2015/16-2018/19 (1 – air temperature, 2 -thickness of snow cover, and 3-estimated depth of freezing of the ground under the snow cover 4-estimated depth of freezing of exposed ground).

The calculation method used is well physically justified. The method solution describes well the process of changing the freezing depth during the winter season. The successful operation of the method needs to set the initial data as accurately as possible. The consistency of the method was proven in the work [4].
Results of calculating the maximum ground freezing depth for a weather station Terskol for the winter periods 2015/16-2019/20 are shown in Table 1.

Table 1

Changes in the maximum ground freezing depth, average snow cover thickness for February, and the sum of negative monthly temperatures for a weather station Terskol for winter periods 2015/16-2019/20

Winterperiod	Sum of negative monthly temperature, °C	Averaged February snow cover thickness, cm	Max. freezing depth of snow-covered ground, cm	Max. freezing depth of exposed ground, cm
2015/16	-18,7	60	21	97
2016/17	-27,7	40	23	119
2017/18	-14,2	70	8	83
2018/19	-19,4	60	20	96
2019/20			20	

Conclusion

The thickness of the accumulated snow cover can reach half a meter or more. At the same time, the ground under the snow-covered surface freezes, according to calculations, by an average of 20 centimeters or more. In the case of partial or complete blowing off of the snow cover, freezing of the ground can occur to a depth of 1 meter or more and last for a longer period. Thus, the proposed method for calculating the dynamics of the depth of soil freezing based on data on air temperature and snow cover thickness allows us to assess the freezing of soil as a factor of soil stability during the construction of avalanche protection structures in mountains. Also it is necessary to take into account that for the forecast, we do not have current values of air temperature and snow cover thickness. It may be necessary to use their long-term values (trends in their change) to check the possibility of using this methodology for forecasting.

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Терскөлдегі топырақтың қату тереңдігін есептеу схемасы

Аңдатпа. Қар көшкінін сақтайтын геотехникалық құрылыстарды салу кезінде таулы аудандарда жердің маусымдық және ұзақ мерзімді мұздату жағдайында осы құрылымдарды бекіту және тұрақтылық мәселесі туындайды. Бұл жұмыста Эльбрус аймағында 2015/16-2019/20 қысқы маусымына арналған есептеу схемасы негізінде қар жамылғысы мен ауа температурасының қату тереңдігі мен топырақтың тұрақтылығына әсері бағаланады. Есептеу сызбасы шекарада фазалық ауысуы бар үш қабатты ортаның (қар, мұздатылған және еріген топырақ) жылу өткізгіштік мәселесіне негізделген. Жылу балансының теңдеуіне фазалық ауысудың энергиясы, еріген жерден жылу ағыны, мұздатылған жерге ағу және қар жамылғысы болған жағдайда, қар арқылы атмосфераға өту кірді.

Түйін сөздер: есептеу сызбасы, ауа температурасы, қар жамылғысы, жердің қатуы, таулы аймақтар, құрылыстың тұрақтылығы.

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Вычислительная схема для глубины промерзания грунта в Терсколе

Аннотация. При строительстве лавиноудерживающих геотехнических сооружений в горных районах возникает проблема крепления и устойчивости этих сооружений в условиях сезонного и / или длительного промерзания грунта. В данной статье оценивается влияние снежного покрова и температуры воздуха на глубину промерзания и устойчивость почвы на основе разработанной схемы расчета на зимние сезоны 2015/16-2019/20 в районе Эльбруса. В основу расчетной схемы положена задача теплопроводности трехслойной среды (снег, мерзлый и талый грунт) с фазовым переходом на границе. Уравнение теплового баланса включало энергию фазового перехода, приток тепла из талой почвы и отток тепла в мерзлый грунт и, при наличии снежного покрова, отток тепла через снег в атмосферу.

Ключевые слова: расчетная схема, температура воздуха, снежный покров, промерзание грунта, горные районы, устойчивость конструкции.

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