Application of the calculating scheme for rock freezing depth during geotechnical monitoring on the Anzob pass (Tajikistan)

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Abstract. Rock instability in high-altitude areas is an important risk factor for humans and infrastructure, especially in the context of climate change. The presence of water in the rock leads to a clear increase in the strength of the rock, the effect is enhanced at lower temperatures and a higher degree of saturation. Since the decrease in rock strength due to the phase transition from frozen to thawed state has a great impact on the strength and stability of the rock soil, the paper proposes a model and a numerical method for estimating the depth of rock soil freezing based on data on air temperature and the thickness of the snow cover. The paper also evaluates the effect of air temperature and snow cover on the rock soil stability and depth of freezing according to the proposed calculation algorithm which is applied for the winter periods 2010/2011-2019/2020 at the Anzob pass in Tajikistan. The calculating scheme is constructed according to the three-layer medium thermal conductivity problem (snow, frozen and thawed rock) with a phase transition on the boundary frozen and thawed rock soil. The equation of heat balance contains the heat of the phase transition, the energy of inflow from the thawed rock and the outflow into the frozen rock and, in the presence of snow cover, the outflow into the atmosphere air through it.

1. Introduction
One of the stability factors of mudflow and avalanche-retaining structures during construction in mountainous areas on slopes is the freezing of the underlying base, because in these areas, rocks can be frozen for eight months or more. However, the recent change in air temperature and precipitation (primarily in the form of snow) lead to a change in the depth and duration of freezing of the rock and, as a result, a decrease in its strength properties. In 2016, the Department of Geocryology of Moscow State University organized a stationary geocryological site in the area of the Gissar Range (Anzob Pass, Ziddinskaya Valley). In this territory, 3 geocryological wells with a depth of 3 to 5 meters, equipped with temperature sensors, were drilled. The first two wells are located at an altitude of 3372 m above sea level, the third well was drilled later in 2019 in the Ziddinskaya valley (abs. height 2000 m). Regime observations of the temperature state of soils, geophysical and laboratory work were carried out to determine the composition, structure and properties of frozen soil. According to thermometric observations, seasonal freezing of soils in this area on the slopes of the northern exposure is observed from mid-October, and continues until the end of April. At the level of 1.5 m, the temperature of the rocks already at the end of May changes from negative to positive, and by the beginning of June, the rocks are completely thawed. Taking into account the snow cover, rock composition and humidity, as well as other factors affecting the freezing depth, the freezing depth was modeled according to the developed calculation scheme. Computational modeling showed the presence of seasonal frozen rocks on the slope of the northern exposure and southern exposure of the...
Anzob Pass at a depth of up to 1.5 m and 1.2 m. In the Ziddinskaya valley, the depth of seasonal freezing does not exceed 1 m. The calculation showed that the gradient of the average annual soil temperature for every 100 m of elevation for the Gissar Range is 0.37°C.

A model study of rock freezing in mountains is presented in [1-5]. In this publication, on the basis of the developed calculation scheme, the depth of freezing of rocks for the last several winter periods is estimated based on data on the thickness of the snow cover and air temperature for the Anzob pass in Tajikistan. The Aznob pass is located at latitude 39.07 and longitude 68.88 with a height of 3373 m above sea level. The average annual temperature at the pass is -2.7°C, but due to heavy snow accumulation, there is no perennial freezing and only seasonal freezing is observed. Calculations of the change in the depth of seasonal freezing of the rock were carried out according to the proposed calculation scheme [6-9] according to the data on the thickness of the snow cover and air temperature based on a three-layer model of the environment (snow, thawed and frozen rock) and assuming a linear change in temperature in the media and heat flow according to the Fourier law.

The paper considered the archival meteorological data on the Anzob Pass weather station available in the public domain on the website "Weather and Climate". And already on the basis of the data on air temperature and snow cover thickness selected from them for the winter periods 2010/2011–2019/2020 (figure 1), calculations were made of the effect of snow cover thickness and air temperature on the depth of freezing of the rock according to the proposed calculation scheme [6-9].

![Figure 1. Changes in air temperature and snow cover thickness according to archival meteorological observation data for the Anzob Pass weather station for the winter periods 2010/2011–2019/2020.](image-url)

The development of calculation scheme of ground freezing on basis of air temperature and snow cover thickness was produced on the observation site of Lomonosov Moscow State University. Therefore, over the past few winter periods, complex studies of snow cover have been carried out at the meteorological site of Moscow State University [6-7] using the method of weekly passage of pits with a complete description of the thickness, stratigraphy and density of the layers that estimate the snow mass in order to create a picture of the temporal dynamics of metamorphism in during the winter period. Thus, weekly observations of the structure and properties of the constituent layers of the snow
mass during the winter period make it possible to describe the dynamics of metamorphism and identify interseasonal patterns. Also, once a month, a trench is traversed, consisting of several dozen observation points and allowing one to establish spatial heterogeneities in the structure and properties of the snow mass. The data obtained allow us to draw conclusions about the spatial and temporal variability of the structure and properties of the snow mass in the conditions of the city of Moscow. It is also assumed that the layers of the snow mass are formed as a result of individual snowfalls. Snowfall is understood as snowfall during one or several days with an intensity of more than 0.1 mm of water equivalent per day.

To study the effect of natural cover (primarily snow cover) on the distribution of the thermal field in the soil on the territory of the Moscow State University meteorological observatory, observations are being made of air temperature, snow cover thickness and the depth of soil freezing using thermometers and permafrost meters of the Danilin and Ratomsky system on a bare site and under a natural cover. Observations have been carried out by the employees of the meteorological observatory, in fact, since its foundation - the date of construction of the main building of Lomonosov Moscow State University, approximately 1960. Recently, work has also been carried out to study the spatial and temporal heterogeneity of the snow mass, as well as modeling is being carried out to assess the effect of snow cover on the depth of soil freezing within the city of Moscow and the Moscow region. In the fall of 2021, a thermometric well 18 meters deep with full core sampling was also drilled at the meteorological site. It is planned to install a thermo-logger in the well to monitor and record the temperature of air, snow cover and soil at different depths.

At the Department of Geocryology, Faculty of Geology, Lomonosov Moscow State University, work on modeling and assessing the effect of snow cover on the temperature regime and seasonal freezing of rocks with the use of computers has been carried out since the 1960s [10]. According to the method and calculation scheme developed by the authors, in this paper, calculations of the thermal field are carried out based on data on the thickness of the snow cover and air temperature using the heat conduction equation for a three-layer environment: snow - frozen soil - thawed soil and with a phase transition at the boundary between frozen and thawed soil. The designed scheme proposes a linear change of temperature in the media [8]. Calculations were made for a number of winter periods of the dynamics of the depth of soil freezing, taking into account the influence of snow cover for the meteorological observatory of Moscow State University [6-7]. A good agreement between the results of calculations and the data of actual observations is shown. The same was also done to assess the depth of rock soil freezing for the mountain Elbrus region (Azau-Terskol) [7]. The obtained results of rock soil freezing depth calculations according to the described calculation scheme on the basis of air temperature and snow cover thickness data for Anzob Pass are displayed on figures 2 and 3.
In the winter period of 2020, on the slopes of northern exposure, the depth of seasonal freezing of the upper part of the section was 1.2 m at an average annual temperature of rocks of 2.42°C (see figure 3).

The applied calculation method is physically sufficiently consistent. The solution according to the method describes well the process of changing the freezing depth during the winter period.

According to calculations, the upper part of the section, this consists mostly of loam, remains frozen under the snow cover at the Anzob Pass from December to April. The thickness of the accumulated snow cover can reach one and a half meters or more. At the same time, the upper part of the section under the surface covered with snow freezes, according to calculations, on average up to 1.5 m.

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