Strength of frozen soils during thawing

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Abstract. More than a third of the Earth’s surface is subject to seasonal or prolonged soil frosts, and the recent warming of the climate requires revision of the construction standards in the conditions of permafrost because under heavy load in low-strength soils, there is a high risk of mobility of thawing rock and collapse of the construction structures, which is fraught with disastrous consequences. For design tasks it is necessary to know the behavior of frozen soils under certain changing conditions. This creates new requirements related to the degradation of permafrost and, as a result, the criteria for strength and stability of soils suitable for construction are changing. Calculation of loads during construction in the permafrost zone requires a special approach in each specific case, since it is impossible to make a single model in connection with the variety of soils and the history of their freezing. Soil typization does not give a clear picture at negative temperatures, since the transition “water-ice-water” in the soil changes the behavior of the grounds, and the unpredictability of climatic changes affecting this process greatly complicates the task. In the hydraulic laboratory of the RUDN University, a series of experiments was conducted for various types of soil subject to load, in order to determine the main parameters affecting the stability of soils during thawing, and to give approximate recommendations regarding the use of these soils as bases.

Key words: permafrost, frozen soil, thaw, strain, strength.

1. Introduction

The behavior of frozen soils is complex and depends on many factors. When formulating the strength to fluidity relation it is important to understand the characteristics of the evaluated soil. This requires a number of laboratory studies, which will then allow to determine the specific parameters of the soil in engineering design. Granulometric composition, load resistance, temperature, moisture content – this is not a complete list of aspects that must be taken into account when designing construction and analyzing base deformations in the conditions of the permafrost.

Freezing and thawing of soil can lead to serious geotechnical, hydrological, and environmental problems. Each soil has its own specific freezing characteristics, mainly depending on the texture and prevailing concentration of solute. Fine-grained soils tend to form ice lenses when frozen, which causes the soil to rise; in a rough texture, ice is more evenly distributed in the substance. Also the behavior of the soil is always closely related to the prevailing meteorological conditions. The hydraulic conductivity of soils decreases as they freeze, which leads to the reduction of infiltration and delay in replenishing groundwater supplies during snowmelt. For larger areas (catchments), the influence of frozen soils on infiltration and runoff is uneven.

The existence of the perennial frozen soils was described in the mid-17th century by M. V. Lomonosov (1711-1765), who proposed the first scientific explanation of permafrost [1], but the first publication about the existence of permafrost was published by von Baer in 1838 [2]. In 1927, Sumgin published the state of permafrost study at that time [3]. In recent years, new problems related to
warming have emerged, which leads to the degradation of permafrost. Problems with slope stability have been reported in mountain conditions [4], and further impacts on Arctic infrastructure are predicted due to climate change [5, 6], including coastal zones [7].

When making a classification of frozen soils, it is very important to describe the presence of water in a particular soil within the current temperature regime. Not always frozen rocks are permafrost. In fact, seasonally thawed in winter or temporarily frozen (for example, in laboratory conditions) soils are of significant engineering interest, but cannot be defined as permafrost.

The original engineering classification of frozen soils was introduced in [8]. The system divides ice in frozen soils into three main groups: 1) spot ice that is not visible to the eye, 2) spot ice that is visible to the eye (<1 inch thick), and 3) ice (ice lenses that are more than 1 inch thick). But this classification is suitable for ice inclusions with limited dimensions. The larger the grain size is, the greater the thickness should be considered as a typical layer. Weaver [9] proposed to classify frozen soil on the basis of bulk density and registered creep mechanism (Table 1).

| Description            | Bulk density [mg/m³] | The mechanism of creep                              |
|------------------------|----------------------|-----------------------------------------------------|
| "Contaminated" ice     | 0.9-1                | Enhanced diffusion (there may be a stable state), recrystallization |
| Significantly "contaminated" ice | 1.0 - 1.5             | Dislocation is inhibited by soil particles (still unstructured) |
| Inviscid frozen soil   | 1.6 - 1.95           | Creep due to the presence of unfrozen water         |
| Viscous frozen soil    | 1.95-2.3             | Creep damping is held back by the soil structure    |

As a rule, when the soil state changes from unfrozen to frozen, the structure of coarse-grained soil particles changes smoothly as the water in the pores freezes. As the water phase changes, the volume increases by 9%, and since the hydraulic conductivity of coarse-grained soil is high, excess water flows off, and the soil structure remains unchanged. On the other hand, fine-grained soils are characterized by lower hydraulic conductivity, which leads to the accumulation of moisture, which increases in volume during freezing. An increase in soil volume due to freezing usually leads to a rise in the level, and excess pore water that occurs during thawing leads to loss of strength and significant deformations. Therefore, these soils are classified as heaving, i.e., sensitive to frost and thaw.

For today, there is a concept of segregational ice formation, which is widely used in engineering practice in the framework of the theory of frost heaving and is the main one for predicting the behavior of soils during freezing. The extremely capacious and versatile problem of segregational ice formation includes many aspects, the main of which are: 1) thermophysical essence of the processes of moisture transfer and ice formation in freezing and frozen soils; 2) mechanisms of moisture migration in freezing and frozen soils; 3) physical-mechanical and physical-chemical transformations in freezing and frozen soils under the influence of moisture transfer; 4) regularities of crystallization of bound and other types of water in the soil, as well as the mechanism of growth of elements of segregational ice; 5) conditions and reasons for the formation of various segregational ice textures and their cryolithological and paleogeographic significance [10].

The article [11] suggests that migration of unfrozen water and segregational ice formation during shear in frozen soils occur as a result of micro-cracking under the action of shear stresses exceeding the value of the maximum long-term strength, i.e. under conditions of non-damping creep, at deformation rates comparable to the migration of unfrozen water rates. Ice slots formed in cracks “heal” them, thereby preventing their growth and delaying the destruction of frozen soil. If this process were absent, the frozen soil would collapse faster. Therefore, it has strengthening nature.
Perhaps this explains the fact that usually when the creep is undamped, the stage of progressive flow of frozen clayey soils has a longer duration than the stage of unsteady creep.

2. Materials and methods

Heaving soils [12] are characterized by the amount (deformation) of frost heaving, \( h_f \), which represents the height of raising of the layer of freezing soil surface and the relative heaving \( f \), determined by the formula (1).

\[
f = \frac{h_f}{d_f},
\]

where \( d_f \) is a layer of freezing soil subject to frost heaving.

The following classification of the degree of soil heaviness is given in [13] (Table 2):

| Name of soils and limits of normative values of the plasticity number | Value of the heaviness parameter \( R_f \times 10^2 \) for soil |
|--------------------------|-----------------------------------------------|
| practically not heaving \( f \leq 0.01 \) | slightly heaving \( 0.01 < f \leq 0.035 \) | medium heaving \( 0.035 < f \leq 0.07 \) | highly heaving \( 0.07 < f \leq 0.012 \) | excessively heaving \( f > 0.12 \) |
| Sandy loam \( I_p \geq 0.02 \) | < 0.14 | 0.14 – 0.49 | 0.49 – 0.98 | 0.98 – 1.69 | > 1.69 |
| Sandy loam \( 0.02 < I_p \leq 0.07 \) | < 0.09 | 0.09 – 0.3 | 0.3 – 0.6 | 0.6 – 1.03 | > 1.03 |
| Loam \( 0.07 < I_p \leq 0.17 \) | < 0.1 | 0.1 – 0.35 | 0.35 – 0.71 | 0.71 – 1.22 | > 1.22 |
| Loam \( 0.07 < I_p \leq 0.13 \) | < 0.08 | 0.08 – 0.27 | 0.27 – 0.54 | 0.54 – 0.93 | > 0.93 |
| Loam \( 0.13 < I_p \leq 0.17 \) | < 0.07 | 0.07 – 0.23 | 0.23 – 0.46 | 0.46 – 0.79 | > 0.79 |
| Clay \( I_p > 0.07 \) | < 0.12 | 0.12 – 0.43 | 0.43 – 0.86 | 0.86 – 1.47 | > 1.47 |

The \( R_f \) value is calculated using the formula (2), in which the density of dry soil is assumed to be 1.5 t/m\(^3\); if the soil density is different, the calculated \( R_f \) value is multiplied by the ratio \( \frac{\rho_d}{1.5} \), where \( \rho_d \) is the density of the dry investigated soil, t/m\(^3\).

According to the degree of frost danger, all heaving soils are divided into five groups, shown in figure 1. The belonging of clay soil to one of the groups is estimated by the \( R_f \) parameter, determined by the formula (2).

\[
R_f = 0.012(\omega_0 - 0.1) + \frac{\omega(\omega - \omega_{cr})^2}{\omega_L \omega_{cr} / M_0}
\]

where \( \omega \) is humidity within the layer of freezing soil, corresponding to the natural; \( \omega_0 \) is humidity at the yield point; \( \omega_{cr} \) is soil moisture, at which the soil is located on the border of the solid and plastic states, share of unit;
\( \omega_{cr} \) is calculated critical humidity, below the value of which the redistribution of moisture in the freezing soil stops, share of unit, determined by the graph in figure 2;

\( M_0 \) is dimensionless coefficient numerically equal to the absolute value of the average winter air temperature when the surface of the freezing soil is open.

**Figure 1.** Correlation between the parameter R(f) and relative deformation of heaving.

**Figure 2.** The value of the critical humidity \( \omega_{cr} \) depending on the number of plasticity \( I_p \) and yield point \( \omega_i \) of soil.
The study of thawing of frozen soil samples was carried out in laboratory conditions at a temperature of 18-20 °C. 5 soil models were prepared, different in their physical characteristics, namely:

1. Moistened sand (coarseness 0.2mm);
2. Moisten peat in equal parts with sand (coarseness 0.2mm);
3. Moisten peat;
4. Peat with sand (coarseness 0.2mm) of natural humidity;
5. Peat of natural humidity.

The shapes for all samples were the same and had the following dimensions – 0.28 m x 0.18 m x 0.08 m (L x W x H). Before laying the models, they were kept for several days in the freezer at a temperature of –18°C until completely frozen. Then the samples were placed in the same conditions and subjected to the same load, equal to 6.2 kg (Figure 3). Thus, we have obtained an analog of the load on the soil during thawing of the rock in the conditions of thawing of the soil.

Since in frozen soil all moisture passes into ice, the ice content of the sample was determined as the ratio of the mass of moisture to the mass of the frozen soil sample before the experiment, and the mass of moisture was obtained by subtracting from the mass of the frozen soil sample a dry substance from the same sample after complete drying, or [14]:

$$I = \frac{M_w}{M_f} \tag{3}$$

where $M_w$ is mass of water in the sample, $M_f$ is mass of the frozen soil sample.

### 3. Results and discussion

At the end of the experiment, when the ice melted, it was possible to estimate the degree of subsidence of the load depending on the type of soil and its ice content (Figure 4). The figure shows the very first sample - moistened sand, which gave the most noticeable subsidence during thawing. The remaining samples did not show any significant difference in levels before and after the experiment.

All measurement results are shown in table 3.

| No. | Type of soil                                  | Ice content (ice/volume), share of unit | The subsidence of the load (m) |
|-----|-----------------------------------------------|----------------------------------------|-------------------------------|
| 1   | Moistened sand                               | 0.12                                   | 0.1                           |
| 2   | Moisten peat in equal parts with sand         | 0.34                                   | 0.08                          |
| 3   | Moisten peat                                 | 0.36                                   | 0.02                          |
The table shows that all other things being equal, sandy soils with minimal ice content are more prone to subsidence. More cohesive soils, such as peat, have shown greater resistance to loads. However, for them, at the end of thawing, cracking is observed (Figure 5), which during operation can lead to the crumbling and collapse of the foundations, especially on the slopes and shores of water bodies.

| No. | Type of soil                        | Ice content (ice/volume), share of unit | The subsidence of the load (m) |
|-----|------------------------------------|----------------------------------------|-------------------------------|
| 4   | Peat with sand of natural humidity | 0.38                                   | 0.01                          |
| 5   | Peat of natural humidity           | 0.53                                   | -                             |

Figure 4. Comparison of the load level before the experiment and after.

Figure 5. Deformation of the sample under load after the end of the experiment.

Scott [15] conducted field research on several rivers in Alaska. He concluded that the rate of thawing of an underwater coastal slope depends on the texture of the material and the temperature of the water. The results of his observations show a general tendency for erosion to lag behind thawing. At the same time the comparison of erosion rates and thawing rates on two specific rivers in Alaska...
showed equal results, regardless of soil properties (Figure 6). These are just the cases when the negative temperature played a dominant role, not allowing the ground to thaw.

![Figure 6. Comparison of thawing and erosion rates on the example of Alaskan rivers.](image)

However, the recent warming of the climate requires studying the behavior of permafrost in new conditions. The Figure 7 shows the area inside the solid line marks where permafrost exists today in the Arctic. The dotted line shows where the permafrost boundary might be by the year 2090. Permafrost in southern areas may thaw because of climate change [16].

![Figure 7. Map by Hugo Ahlenius, UNEP/GRID-Arendal; courtesy Arctic Climate Impact Assessment (ACIA), 2004 Impacts of a Warming Arctic.](image)
Different authors and researchers give completely contradictory results of their research of permafrost, often getting different conclusions within the same object. In our experiments, it turned out that a large ice content during its thawing is a guarantee of greater soil strength, and not only being in a frozen state, which leads to cementing the earth during construction. A much larger role here is played by the connectivity and strength of the soils. Porous cohesive soils are able to retain a large amount of moisture, which leads to increased ice content and heaving of the bases, but such soils keep their strength properties during thawing due to the adhesion of soil particles, which is observed in our experiments. To reduce humidity and as a result, the ice content of the rock, it is advisable to mix cohesive soil with non-cohesive, such as sand. Sand fills the pores by entering such a soil as a grid, and when this mixture is moistened, less water accumulates in it due to filling the pores. This leads to a decrease in ice content and heaviness. In any case, the task requires further development.

4. Conclusions
The strength of the thawing soil is affected by many factors, such as ice content, connectivity, flowability, porosity. In conditions of negative temperatures, ice content is a strengthening factor similar to hard rocks. In the conditions of thawing of rocks for the stability of the soil the determining factor is its connectivity. To reduce the ice content of the soil, it is recommended to introduce into the composition of the soil non-cohesive soil (for example, sand), whose particles will fill the pore space and thus reduce the water-holding capacity of the soil. Lowering the ice content in addition to reducing soil deformations during thawing will also reduce the heaviness during freezing, i.e. such a mixture of soils will be more stable under seasonal weather changes.

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