The influence of the water flow on the stability of the coastal slope and adjacent transport constructions

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Abstract. The mechanical behavior of the frozen soil is dynamic and complex. When formulating the strength-to-deformability ratio, it is important to understand the characteristics of the soil, which is being estimated. At the same time different soil samples that have analogical physical characteristics in the unfrozen state may behave differently after freezing and during thawing, as frozen relict and seasonally thawed soils behave differently. All this requires a number of laboratory researches, which will then allow to determine the soil parameters for a specific project. In the hydraulic laboratory, experiments were conducted to study the strength of the different samples of frozen soil under the influence of the water flow and the same load.

1. Introduction
In recent years, attempts have been made to create classifications based on the division of the hydraulic structures located in riverbeds and floodplains into active and passive ones and the degree of their impact on the channel processes. An example is the classification of Snischenko [1]. The first category includes: dams, bridge crossings that overlap floodplains, weaning of runoff from rivers and flooding of rivers during the transfer of runoff, and the second — river embankments hundreds of kilometers long, which completely separate the riverbed from the floodplain and radically change the channel processes of these river sections. Objects such as bridge crossings that overlap floodplains change channel processes on long river sections.

It should be emphasized that channel processes react most quickly and acutely to anthropogenic impact, and the degree of this impact can currently be so great that it radically changes the channel process on a water object.

Unfortunately, the methods of calculations and forecasts of channel processes have not yet been developed sufficiently.

All types of anthropogenic impacts can be conditionally divided into three groups:
- the impact on the climate;
- a set of activities in the river basin;
- various types of constructions and activities in riverbeds and floodplains.

The first group has an indirect effect on runoff and other hydrological parameters through precipitation, sediment flow to streams and rivers, and other factors. More specific is the anthropogenic impact on river basins, as well as the impact of hydraulic constructions and water management measures in riverbeds and floodplains on the hydrological characteristics of a water object.

Various researchers have repeatedly noted that a water object is a self-regulating system. That means that a change in some hydrological characteristics in one place (for example, embankments, ditches in the floodplain, riverbed constraint due to the building of bridges) leads to a change in the balance of flow and sediment downstream, or even to significant washouts and niche formations, which clearly affects the stability of the nearby constructions. Traditionally, frozen rocks in the cryolithozone were considered to have stability comparable to hard rock, and such assumptions were used in the building of the hydraulic constructions and bridge crossings. However, the climate warming and the associated with it processes of the degradation of frozen soils have forced to review the basic construction standards. In [2] it was noted that the frozen soil during thawing loses its strength properties to a degree even less than the similar structure soil in the middle latitudes.

In recent years, new problems related to the degradation of permafrost initiated by an increase in soil temperature have emerged. Slope stability problems have been reported in mountain environments [3], and a new impact on the Arctic infrastructure is expected [4] and coastal zones [5] with the consequences of climate change [6].

2. The purpose of the work
The observed climate warming requires a review of the standards of construction near rivers and other water objects, since at high loads in low-strength soils there is a high risk of mobility of thawing rock and collapse of construction structures, which is fraught with catastrophic consequences. For the tasks of design in the conditions of the cryolithozone, it is necessary to know the behavior of frozen soils under various changing conditions. In this regard, new requirements related to the degradation of permafrost arise and, as a result, the criteria for strength and stability of soils suitable for construction are changing. The purpose of this work is to study various soil samples for stress resistance under thermal (natural thawing) and mechanical (water flow influence) influences.

3. Materials and methods
Physical modeling was performed on a hydraulic circulation tray with the following parameters:
- length – 4.5 m, of which 1.5 m was selected as the working area for installing models;
- width – 0.6 m;
- depth – 0.2 m.

To create a model close to natural conditions, 0.2 mm size sand was placed on the bottom of the tray. The samples of beforehand (several days in the chamber at a temperature of -18°C) frozen soil of 5 different physical characteristics were laid in such a way that they were embedded in the river bank of the water stream. On the each sample the load of the same shape and weight (6.21 kg each) was put. This is shown in Figure 1.

The width of the stream after the model was laid was 0.35 m. The depth was 0.04 m, which was equal to half the height of the models. Herewith the surface speed of the flow was 0.2 m/s.
The shapes for all samples were identical 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. The soil models differed in the following characteristics:
1. Moistened sand (particle size 0.2 mm.);
2. Moistened peat in equal parts with sand (particle size 0.2 mm.);
3. Moistened peat;
4. Peat with sand (particle size 0.2 mm.) of natural humidity;
5. Peat of natural humidity

**Figure 1.** The laboratory experiment.

**4. The laboratory experiment**

Within a few minutes after the experiment started, the direct influence of the water flow could be noticed, which was expressed in the erosion of the submerged in water part of the sample (Figure 1). In [7] it was shown that thawing occurs slightly faster than the erosion itself. For different types of soil, the value of the thermal conductivity coefficient increases with the increasing of the ice content. All things being equal, the rate of thawing increases in the direction: clay – sandy loam – sand.

Also in [7] the measurements of thawing and erosion for a time were made, and the graphics of various freezes soil thawing and the erosion graphics were plotted for each experiment depending on time. The resulting graphs are uniquely interpolated by a logarithmic dependence (Figure 2).

**Figure 2.** The movement of the thawing front (logarithmic approximation) – dotted line – for wetted soil, point – for natural wet soil; solid line – the movement of the erosion front.
The graphs show that the time of the beginning of erosion does not coincide with the time of the beginning of thawing, thawing begins earlier, and at the same time thawing is about twice as fast. Thawing of various soils, such as frozen natural soil (analogous to the above-water slope) and frozen wetted soil (analogous to the underwater part of the slope), differ by about one and a half times.

Only the area in the water is subject to erosion. After the start of erosion, the upper, above-water part of the slope begins to sink and collapse. In our experiments, the load-bearing capacity of the soil models during thawing and the influence of water flow gradually decreased, which resulted in a collapse in the following sequence: 4→5→1→2→3. Figure 3 shows the load on the sample that showed the highest strength characteristics, and Figure 4 shows the state of the riverbed at the end of the experiment after the impact of the flow and loads on the thawed areas.

**Figure 3.** The gradual collapse of the load in the thawing of the framework process.

**Figure 4.** Deformations of the coastal slope under the influence of the flow and load.

### 5. Results and discussions

As a result of the experiment, moistened peat showed the greatest strength characteristics. This is due to the fact that the thawing of the contained in it ice occurs much slower than the thawing of the ordinary peat with high porosity. When such a sample is placed in the stream, water fills the pores and washes out the substance, and the pores of the above-water part are filled with ambient air, which also contributes to rapid defrosting of the sample.

In second place in terms of stability was moistened peat in equal parts with sand, which also can be explained by the cementing effect of frozen moisture. This sample thawed more slowly than a similar
sample of natural humidity, which is also explained by filling the pore space with water or air. Moistened sand was held only by the adhesion of ice, and at thawing it immediately crumbled, which is quite obviously due to its loose properties.

Thus, the strength properties of various soils are described by many factors, including porosity and ice content. In our case, it was not possible to obtain relict ice, which is found in the cryolithozone, but we used an analog of the seasonally thawed layer of soil. This work is a continuation of previously started studies of deformations of the coastal slopes of Northern rivers, where the dependence of collapses on flow rates, the presence of snow cover, rain, and the direction of the coastal slant was established [8] as well as studies of loads on the frozen ground during thawing [9].

According to [10], the degree of thermal shrinkage of perennially frozen rock during thawing is determined by the formula:

\[ \delta = \left( \rho_{d,t} - \rho_{d,f} \right) / \rho_d, \]

where \( \rho_{d,t} \) is density of dry (skeleton) thawed soil that thawed under the design load, g/cm\(^3\); \( \rho_{d,f} \) is density of dry (skeleton) soil in the frozen state, g/cm\(^3\).

In the classification of permafrost soils they are divided into four categories depending on the degree of thermal shrinkage in the base:
1. non-shrinking, durable \( \delta < 0.03 \);
2. low-shrinking, not durable enough \( 0.03 < \delta < 0.1 \);
3. shrinking, soft \( 0.1 < \delta < 0.4 \);
4. high-shrinking \( \delta > 0.4 \), and also containing underground ice in the upper horizons.

The condition of thermal stability of permafrost: the depth of freezing should exceed the depth of seasonal thawing by an average of 10-30% or more, where \( K_s \) is the coefficient of thermal stability:

\[ K_t = t_f / t_h \geq 1.1 - 1.3 \]

Load calculation during hydrotechnical construction in the cryolithozone is a complex task and requires a special approach in each case, since it is impossible to make a single model due to the variety of soils and their freezing history. Soil typification does not provide a clear picture at subzero temperatures, since the water-ice-water transition in the soil changes the behavior of rocks, and the unpredictability of the climate changes affecting this process significantly complicates the task. However, this issue requires further research.

6. Conclusion
- The main suggestion is not to build roads on floodplains (the part of the river valley that is above the riverbed and is flooded during high water or during floods). This also relates to wetlands.
- When designing bridges, observed flood data should be taken into account, meaning that bridges should not be turned into dams. Take into account changes in the type of the riverbed processes and general erosion that occurs during the periods of flood runoff.
- Apply a method for calculations that takes into account both the mass transfer between the riverbed and the floodplain, and the effect of interaction between the riverbed and floodplain flows.
- Keep in mind that the accumulation of the sediment in front of the bridge leads to an increase in the erosion of the riverbed outside the bridge. This leads to coastal deformations and destruction of the coastal anchorages.
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