Research on the Hydraulic Conductivity Properties of the Soil Subgrade of the Central Yakutia

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Abstract. This work presents the results of research on the effects of compaction, moisture content and temperature on the coefficient of hydraulic conductivity of frozen and not frozen soils. Moisture permeability - the property of non-saturated soil to pass through its pores a non-continuous stream of water under the influence of moisture gradients, which provide gradients of absorption force. These forces arise due to the interaction of water with the surface of mineral particles and air. This is more a diffusion process than a filtration process. Clay soils of the earth bed within the depth of the seasonal thawing layer were selected for conducting studies of moisture-conducting properties of soils. Three series of tests were conducted. During all three series of tests graphs of dependence of coefficient of moisture conductivity (KW) are constructed and corresponding conclusions are drawn. When establishing experimental regularities, statistical data of experiments performed with 5-fold repetition were analyzed. Conclusions are reached concerning the migration of moisture in frozen and not frozen soils.

1. Introduction
Prediction of the estimated soil moisture of the subgrade is of great importance in the design of road structures, which subsequently affects the durability and reliability of the transport structure. The values of the calculated humidity are established on the basis of data from long-term observations of the water-thermal regime of the soil of the subgrade of roads, and can also be determined on the basis of the forecast.

The development of methods for assessing and determining the bearing capacity of soil foundations during the construction of engineering structures involved many scientists such as Z.G. Ter-Martirosyan, N.N. Maslov, E. Zaharesku, G.E. Meerhof, K. Terzagi and others [1 – 7].

For Siberia and the far east of Russia, characteristic features are seasonal changes in the water-thermal regime of the subgrade with excessive moisture (0.75-0.85 WT) and deep freezing of the soil (more than 1.5 m) which have a significant impact on the ability of the road structure clothes to transfer and distribute the traffic load. These changes are especially noticeable when loamy and loamy soils lie at the base of the road [8 – 11].

During the spring thawing of the soil, its water saturation occurs. This is the most dangerous period, which is taken as the estimation for the design of pavement. In the upper part of the subgrade and the underlying soil, the bases formed during the winter, the ice lenses thaw, and the pores of the soil are
filled with free water. The resulting soil layer retains for a certain period of time the maximum humidity \( W = (0.85 \div 1.0) \) WT, the minimum density and strength of the soil.

During this period, the design of pavement is especially weakened:

- Firstly, soil curbs thaw much slower than the carriageway and the underlying layers of pavement, as a result of which thawed moisture accumulates in the layers of the structure, which leads to their water saturation.
- Secondly, a three-layer structure is formed of thawed layers of the pavement structure, a water-saturated subgrade layer and a layer of frozen ice-saturated soil, which is not able to fully absorb and transmit the load.
- Finally, in the presence of an underlying hard layer, and ice-rich soil can be considered hard, stress concentration occurs.

Therefore, in the construction of roads in Siberia and the Far East of Russia, as well as in countries such as the USA, Canada, and Norway, it becomes necessary to predict the moisture content of subgrade soils to increase the reliability and performance of the structure. In this case, analytical methods for calculating humidity are often used, based on the laws of moisture migration in soil massifs when the temperature front changes. In this case, the main design characteristic that determines the moisture accumulation in soils is the value of the coefficient of moisture conductivity. It should be noted that the laws of moisture change in soils that are in the permafrost state or undergoing deep freezing are still not fully understood. That is why the main purpose of the study is to determine the coefficient of moisture conductivity and weighted average moisture accumulation of soils in the calculation period and at negative soil temperatures.

2. Theoretical framework

To implement the research on the hydraulic conductivity of selected clay soils of a subgrade layer which is subjected to seasonal thawing, laboratory studies were conducted at the Highway and Airport Department of the M. K. Ammosov North Eastern Federal University. The results of the studies of particle size grading and the physical properties of the soils are presented in Table 1 - Table 3.

### Table 1. Particle size grading of the studied soils.

| Type of soil         | Particle size composition (content of particles by %, diameter in mm) |
|----------------------|---------------------------------------------------------------------|
|                      | 10-5  | 5-2  | 2-1  | 1-0.5 | 0.5-0.25 | 0.25-0.1 | <0.1 | Σ                       |
| Plastic sandy loam   | 14.055| 21.694| 15.474| 14.772| 17.093   | 11.12    | 5.715| 99.926                  |
| Light silty loam half-hard | 0.22  | 0.95  | 12.79 | 17.22  | 16.72    | 15.21    | 35.52| 98.63                    |
| Heavy clay           | 0.21  | 4.22  | 14.57 | 11.79  | 9.98     | 11.31    | 47.5 | 99.58                    |

### Table 2. Physical properties of the studied soils.

| Type of soil         | Density \( \rho \), g/cm³ | Moisture content, prop | Plasticity index \( I_p \), prop | flow index \( I_L \), prop |
|----------------------|-----------------------------|------------------------|----------------------------------|---------------------------|
| Plastic sandy loam   | 2.16                        | 0.162                  | 0.213                            | 0.172                     | 0.042                     | 0.002                     |
| Light silty loam half-hard | 2.06  | 0.198                  | 0.275                            | 0.155                     | 0.119                     | 0.004                     |
| Heavy clay           | 2.01                        | 0.172                  | 0.309                            | 0.701                     | 0.39                      | 0.014                     |

Determination of the coefficient of hydraulic conductivity is regulated by current normative standards using the method of Professor N. A. Zolotar with the device PKVG-Futurum (Figure 1) [12, 13].
Table 3. The resulting diffraction patterns.

| Mineral composition         | Quartz, % | Kaolinite, % | Albite, % | Basan, % |
|----------------------------|-----------|--------------|-----------|----------|
| Plastic sandy loam         | 60.25     | 25.2         | 9.32      | 5.23     |
| Light silty loam half-hard | 62.66     | 8.95         | 24.21     | 4.18     |
| Heavy clay                 | 61.84     | 11.92        | 22.14     | 4.1      |

Figure 1. Diagram and photograph of the apparatus PKVG-F for the calculation of the coefficient of hydraulic conductivity of soils.

The mineral composition of the tested soils held at the Institute of Mining of the North SB RAS in the mineral processing laboratory diffractometer D8 Discover [14]. The resulting diffraction patterns are shown in the graphs (Figure 2).

The given method provides for the calculation of the value of the coefficient of hydraulic conductivity, through measuring the initial values of the soil moisture and density, and the time required to achieve dampening of the front upper surface of the sample when moistened from below.

During the tests, the following boundary conditions apply:

- the initial moisture content and density are uniform throughout the volume of the soil sample [15];
- the soil sample, to be moisturized through the bottom surface, has a stable initial moisture content of the upper surface; with the arrival of the moisture to that surface the experiment is completed;
- moistening of the soil sample occurs in an unpressurized mode at a constant rate [16].
The preparation of cylindrical samples of broken structure and of given density and moisture is performed in accordance with the requirements [17, 18]. The height of the soil sample must equal the height of the cylindrical container: 7 cm. The diameter of the sample must also equal 7 cm.

The density of the dry soil test sample is related to its mass dependency:

$$\rho_c = \frac{m}{V(1+W)}$$  (1)
where $\rho_c$ – density of the dry soil gr/cm$^3$; $m$ – mass of the sample, gr; $V$ – volume of the sample, cm$^3$; $W$ – moisture content of the soil, prop.

For given values of time $\tau$ and mass $m_w$ of the absorbed water, the computation of the coefficient of hydraulic conductivity of soil $K_W$ is [19]:

$$K_W = \frac{4}{3.14 d^4 \tau} \left[ \frac{m_w}{\rho_c (W_{IIB} - W_H)} \right]^2$$  \hspace{1cm} (2)

where $W_{IIB}$ - full moisture capacity of the given soil, which is calculated by the formula

$$W_{II} = \frac{1}{\rho_d} \left( \frac{1}{\rho_s} - 1 \right)$$  \hspace{1cm} (3)

where $\rho_d$ – density of the dry soil gr/cm$^3$; $\rho_s$ – density of the part of the soil specified: for sandy loam – 2.68, loam – 2.70, clay– 2.72, gr/cm$^3$; $\tau$ – time of moistening, hr; $m_w$ – mass of the absorbed water, gr; $W_H$ – initial moisture content of the tested soil; $d$ – diameter of the soil sample, cm [13].

To establish the experimental patterns, statistical data were analyzed from five replications of the experiments.

3. Materials and methods

The methodology provides for the determination of the coefficient of moisture conductivity at initial humidity and density during the humidification time necessary for the distribution of humidity in the sample - from the total moisture capacity in a single elementary volume on the surface in contact with the liquid to the initial moisture content at its boundary. The sample is humidified below the water level maintained from below. The method involves the following boundary and initial conditions:

- The initial moisture and density of the sample should be evenly distributed over its volume.
- When moistening the sample through the lower surface, a change in humidity on its upper surface is not allowed when the moistening front approaches it.
- Moistening of the sample should be non-pressure.

This work presents the results of research on the effects of compaction, moisture content and temperature on the coefficient of hydraulic conductivity of frozen and not frozen soils. Three series of tests were conducted:

Series 1 – Research on the effects of the degree of compaction of not frozen soil on its coefficient of hydraulic conductivity. Samples of sandy loam, loam, and clay were tested with an initial moisture content (W$_H$) of 8% and rates of compaction of 0.95, 1.00, 1.05 and 1.10 at a temperature of 25 °C.

Series 2 - Research on the influence of the initial level of moisture content on the coefficient of hydraulic conductivity of not frozen soil. Samples of sandy loam, loam, and clay were tested with initial moisture contents (WH) of 8%, 12% and 16%.

Series 3 - Research on the dependence of the coefficient of hydraulic conductivity on the temperature of frozen soil. Samples of sandy loam, loam, and clay were tested with an initial moisture content (WH) of 12% in a range of negative temperatures from minus 1°C to minus 4°C.

4. Results and discussion

Series 1 results are plotted in the graph of the dependency of the coefficient of hydraulic conductivity (KW) on the degree of compaction (Купл) of not frozen soils at the initial moisture content (WH) of 8% and the temperature of 25 °C (Figure 4.).
Series 2 results are plotted in the graph of the dependency of the coefficient of hydraulic conductivity (KW) on the initial moisture content (Wн) of the not frozen soils at a temperature of 25° C (Figure 4).

In the third series of experiments, samples of sandy loam, loam and clay were frozen with an initial moisture content (WH) of 12% and with a compaction factor of 0.95. Freezing of the soil in the refrigerating chamber at a temperature of - 6 °C lasted 24 hours. After the freezing of the samples, the
coefficients of hydraulic conductivity (KW) of the samples of frozen sandy loam, clay loam and clay which had been moistened from below at a temperature of -4 °C to -1 °C, were calculated.

The graph of the dependency of the coefficient of hydraulic conductivity (KW) of the frozen soils, on temperature, is shown in figure 5.

![Figure 5. Graph of the dependency of the coefficient of hydraulic conductivity (KW) on the temperature of the frozen soil.](image)

5. Conclusion
1. The type of soil and the degree of its compaction have great significance for capillary lifting of moisture. The research shows that the coefficient of hydraulic conductivity (KW) of soil depends on the degree of its compaction [17, 18]. Consequently, the increase in the degree of compaction of soil subgrade is one of the most effective measures to stabilize the water and thermal conditions of the road structure. From the graph of the dependency of KW=f(Kупл) (Figure 2) it is seen that given the same initial moisture content (WH), when the compaction factor is increased from 0.95 to 1.10, the magnitude of the coefficient of hydraulic conductivity (KW), becomes 2-3 times higher [20]. This is explained by
the decrease in the total pore volume and mobility of the water in the remaining pores, which hinders the flow of water through the soil.

2. A comparison of the graphs of \(KW=f(WH)\) (Fig. 3) shows an increase in the coefficient of hydraulic conductivity when transitioning from fine to coarse rock. For example, with the same initial moisture content of 16\%, the coefficient of hydraulic conductivity for sandy loam is 30 times more than for clay. At the same time, the increase in the coefficients of hydraulic conductivity with the increase of the initial moisture content of the samples is due to the increase in the prevalence of the share of the capillary and free moisture over the less mobile related. Consequently, the presence of finer moisture conveying capillaries in the clayey soils leads to smaller values of the coefficients in comparison with loam.

3. A comparison of graphs \(KW=f(Kupl)\) (Fig. 2) and \(KW=f(t)\) (Fig. 4) shows that the value of the coefficient of hydraulic conductivity (KW) of frozen clay is 1.5 times lower than the average of not frozen clay with the same initial moisture content (WH) and extent of compaction, due to the crystallization of a significant amount of moisture at low temperatures and the decrease of its mobility. The highest (extreme) values of the hydraulic conductivity coefficient (KW) of unfrozen water are confined to temperatures from -2 to -3 °C. In this temperature range the flow of unfrozen water in frozen ground and formed micro-schliere, is sharply reduced, eventually turning into a solid ice interlayer.

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