RESULTS OF PHYSICAL SIMULATION OF FROST HEAVING IN SOILS

V.G. Cheverev, E.D. Ershov, M.A. Magomedgadzhieva, I.Y. Vidyapin

Department of Geocryology, Faculty of Geology, Moscow State University, Vorob’evy Gory, 119234, Moscow, Russia.
e-mail: chuvin@geol.msu.ru

Abstract

A procedure and a device have been developed for determining the chemical potential of moisture and some other parameters of moisture transfer in freezing soils. Based on experimental research, new principles of the development of moisture potentials, moisture flow and coefficients of hydraulic conductivity have been established for the frozen and unfrozen parts of freezing soils. The wave-like dynamics of ice redistribution under a temperature gradient were established in frozen soils. It is shown that the relationship between moisture flow and gradient of moisture potential in freezing soils is nonlinear (Darcy’s law does not apply). The results obtained allow mathematical models of the process to be improved.

Introduction

To date, a number of theories of moisture migration in freezing soils have been proposed (e.g., Anderson and Morgenstern, 1973, Orlov et al., 1977). However, their conclusions are contradictory. That is why there is no unified concept of the mechanism of frost heaving in soils and of the basic parameters required to determine the process.

In our opinion, the physics of frost heaving may be described, generally, by dividing a freezing soil into two parts: frozen and unfrozen (Figure 1). The frozen part may be sub-divided into solid- and soft-frozen layers, while the unfrozen part can be divided into layers with shrinkage and without shrinkage.

A motive force for cryogenic migration of moisture develops in the frozen part under the influence of a temperature gradient. Freezing desiccates the soils, releasing the surface energy of mineral particles. As a result, the moisture potential decreases compared to that before freezing. The temperature gradient induces a gradient of moisture potential in the frozen zone which produces a gradient of pore pressure in the unfrozen part. With the passage of time, a layer of transit moisture transfer forms ahead of the freezing front and moisture transfer takes place without a moisture content gradient but is ensured by a gradient in pore pressure (Figure 1, layer which experienced shrinkage). As a result, in the absence of a mechanical obstacle, moisture transfer occurs from the unfrozen to the frozen soil. The moisture arrived to the frozen part is surplus and therefore, it turns into ice. It localizes in the frozen part in the form of ice streaks, thus reducing frost heaving of the soil.

Experiment 1

Procedure

Existing mathematical models of frost heaving in soils may take moisture content gradient as a motive force for the cryogenic migration, and this is incorrect. We studied experimentally the parameters of moisture transfer in freezing soils. We simulated separately the moisture transfer in the frozen and in the unfrozen parts of soils under conditions of steady-state moisture exchange.
The first objective was to develop a procedure and apparatus for determining the chemical potential of moisture in frozen and unfrozen soils. The quantitative relationship between the potential of moisture in a system and the temperature of freezing was deduced by Edlefsen and Anderson (1966):

\[ dP_w = dTL/TV_w \]  

where \( V_w \) is the molar volume of water and \( L \) is the heat of transition between water and ice.

Substitution of \( T \), \( L \), and \( V_w \) of bulk fresh water into equation (1) shows that a change in pressure of 0.1 MPa exerted on liquid water results in a change in its freezing temperature of 0.0824°C. However, using this equation is difficult because of uncertainty in the values of unfrozen water. That is why equation (1) had to be confirmed experimentally.

In developing the investigative procedure, four different tests were performed to determine the moisture potentials known from agrophysics: tensiometric, hygroscopic, osmotic and micro-capillary tests. The capillary pressure was determined using the tensiometric method in the unfrozen part of freezing soils. The osmotic and microcapillary methods did not give useful results for various technical reasons and therefore we obtained the basic data by the modified hygroscopic method which we termed “cryohygroscopic”.

The cryohygroscopic method is based on the fact that in a closed isothermal equilibrium system, the chemical potentials of ice, vapour, and unfrozen water are equal and may be measured in any phase. The moisture content of the sample was measured under a condition of equilibrium between sample and water vapour, by knowing the chemical potential of vapour over a solution of NaCl of known concentration. As standard samples, we used samples of various materials: kaolinite, ceramics, bentonite and filter paper. The specimens were put into desiccators over a solution of known concentration and were controlled thermostatically at various positive and negative temperatures. Equilibrium was reached within 30 days. The unfrozen water content versus temperature was determined using the contact method (Ershov et al., 1979).

Using the data from the tests, we constructed graphs of the time dependence of moisture contents of the standard samples, and then graphs of equilibrium moisture content versus negative temperature and (Figure 2) moisture potential. The relationship between moisture potential and temperature for the samples are shown in Figure 3.

For the next stage of the research, dry standard samples were put into immediate contact with samples of frozen soils under controlled conditions. They remained in this position until equilibrium was achieved. Usually this required one week. In this case, ionic exchange was excluded. Knowledge of the equilibrium moisture content of the standard samples allowed the estimation of the chemical potential of frozen soils.

![Figure 2](image2.png)

**Figure 2.** Equilibrium moisture content as a function of the temperature and moisture potential for samples of kaolinite clay. The data were obtained by sorption from vapours (1), desorption (2), and sorption from ice (3).

![Figure 3](image3.png)

**Figure 3.** Moisture potential versus temperature in samples of kaolinite clay, obtained by sorption (1), desorption (2), and calculated (3) using equation (1).

**INTERPRETATION**

A comparison of the graphs of moisture potential versus temperature, constructed using measured data and calculated from equation (1) showed general agreement, but some discrepancy beyond the limits of experimental error. This is probably connected to differences between the crystallization (latent) heat and the specific volume of unfrozen water in the soils compared to bulk water.

Thus, the possibility of using equation (1) is established experimentally for the approximate calculation...
of chemical potential of moisture in frozen soils as a function of temperature and of unfrozen water content.

**Experiment 2**

**PROCEDURE**

The moisture-exchange properties of the frozen part of the soil were investigated for the soft-frozen layer (in the zone of active water-ice phase transition) under temperatures down to -3°C. The solid-frozen part of the freezing soils was not studied, because the unfrozen water there is essentially immobile.

Tests were performed on water-saturated samples of a silty loam from the Yamal Peninsula, consolidated to a density of 1.52 g/cm³. The samples were cooled to a temperature of -70°C and had a massive cryogenic structure. The samples were 5 cm in diameter and 3.5 cm in height. Testing lasted from 15 hours to 5 days. The sides of each sample were insulated and heat flow was along the central axis. Stability of the heat flow was ensured by control of the boundary conditions: -0.2°C at one end and -3.5°C at the other end of the sample. The dynamics of moisture transfer and redistribution of ice as a function of time was studied using twinned samples. Using the data obtained, we estimated the unfrozen fluxes and the coefficients of hydraulic conductivity of the soft-frozen soils.

**INTERPRETATION**

During the experiment, the unfrozen water migrated towards the region with lower temperatures, as expected (Figure 4). Detailed study of the kinetics of the process showed the following. In the first hours of the experiment, the movement of unfrozen water transfer occurred only in the high temperature part of the frozen layer. With time, it gradually spread into the colder zones. During the course of the experiment, the soil samples were not supplied with external moisture (i.e. the system was closed). Therefore, the moisture (ice) redistribution was damped like a wave and shifted toward the region of the soil with lower temperature. We believe, that this is associated with a decrease in unfrozen water resupply at the expense of a decrease in ice reserves in the warmer part of the sample. Thus, 15 hours after the beginning of the tests, the greatest migratory moisture flux \(2.110^{-4} \text{ m/day}\) was detected in the layer with a temperature of -1.75°C; on the third day, the highest flux \(0.7510^{-4} \text{ m/day}\) was in the layer with a temperature of -2.75°C (Figure 5).

The relationship \(K_p(T)\), obtained after different periods of time, reflects not only the mobility of unfrozen water, but also the whole process (Figure 6). The curves in Figure 6 show the hydraulic conductivity \(K_p\) of unfrozen water as a function of temperature. The hydraulic conductivity decreases as the temperature of the soft-frozen loam is reduced. The coefficient of hydraulic conductivity was 1.3 to \(2.0\cdot10^{-6}\) m/day at
-2.7°C and 4.2 - 4.5•10⁻⁸ m/day at -2.2°C. By extrapolation, the hydraulic conductivity at a temperature of -2.0°C is of 6•10⁻⁸ m/day.

**Experiment 3**

**PROCEDURE**

The hydraulic conductivity of the unfrozen part of freezing soils was examined using apparatus described in Ershov and Cheverev (1981). This consists of a cylinder with an inner diameter of 5 cm and a height of 12 cm. A sample of the soil was placed in this cylinder. The upper surface of the sample was in contact with air flow from a fan and the lower surface was placed in a box containing moist fine-grained sand. Water was supplied to the sand through a measuring glass tube. Several holes were drilled in the cylinder to insert fine-pored ceramic pore-water pressure cells into the sample. These were connected with quick-response pressure cells with the help of thin flexible transparent tubes. The whole pore pressure measurement system was filled with de-aired water. In this procedure, atmospheric pressure was taken to be zero, pressures higher than atmospheric were assumed to be positive and pressures lower than atmospheric were assumed to be negative. A steady-state regime of moisture movement was achieved during each experiment by maintaining a constant evaporation from the upper face of the sample and continuous water supply to its lower face. The distribution of pore-water pressure and the density of the moisture flux (Jw, cm³/cm²s, or cm/s) were then read throughout the height of the sample. After the experiment was completed, the final distribution of moisture and density throughout the height of the sample was determined. The coefficient of hydraulic conductivity (Kp) was calculated using the following equation:

\[ K_p = \frac{J_w}{dP_w/dx} \]  

The tests were performed under various conditions of intensity of evaporation and temperature. This allowed the determination of the relationships between the coefficients of hydraulic conductivity and the density of the moisture flux, and gradients of pore pressure and temperature. Thus it was possible to study relevance of Darcy’s law to moisture migration in freezing soils and to evaluate the role of temperature in this interesting process.

**INTERPRETATION**

During the experiments, the parameters of moisture transfer in the unfrozen part of freezing soils varied within the following ranges: Jw varied from 0.36•10⁻³ to 18•10⁻³ m/day, dP/dx varied from 4 to 144 units (P is expressed in meters of water column), and the temperature of the environment varied from +0.8 to +22°C. All of the pressures measured during the experiment were negative, varying from 0 to -0.07 MPa. It is possible to see an analogy with infiltration in this case, but with negative values for the pressure gradients. In previous experiments, we obtained negative pore pressures in the unfrozen part of freezing frost-susceptible soils. Clearly, the pore pressure of unfrozen water in the frozen soil was also negative. Positive pore pressures occur only in non-frost-susceptible soils when water is expelled from the freezing front, for example, in sands or during very rapid freezing. The pore water removal is more pronounced in this case than its seepage into the zone of freezing.

The results of our experimental investigations are given in Figures 7 a and b. The experimental data show that the relationship between the coefficient of hydraulic conductivity and the pressure gradient is linear when pressure gradients are large and nonlinear.
when pressure gradients are small. Consequently, under certain conditions, Darcy’s law does not apply. The critical pressure gradient depends on the type, density and temperature of soil (Figures 7 a and b). In our experiments, it varied from 20 to 80 units and increased with a decrease in temperature and with an increase in density of the soil. It should be noted that small pore pressure gradients occur naturally during seasonal freezing.

The curves for the coefficient of hydraulic conductivity versus dP/dx, presented in Figures 7 a and b, show the existence of threshold gradients in pore pressure above which moisture transfer occurs. This question is controversial. In our opinion, the threshold pressure gradient is relative to time and depends on duration of freezing. If freezing occurs for a short period of time (seasonal freezing), the threshold pressure gradient is present. If freezing occurs for a long period of time (perennial freezing), the threshold pressure gradient is absent. In the latter case, the greater viscosity of unfrozen water must be taken into consideration. A rheological approach should be taken to solve this problem.

Conclusions

1. A complex procedure and a device were developed to study the parameters of moisture transfer in freezing soils in terms of the physics of the process.

2. The possibility of using equation (1) for approximate calculation of the moisture potentials in frozen soils was proved experimentally.

3. The wave-like attenuating pattern of moisture transfer and segregated ice formation were established for the frozen part of freezing soils under a temperature gradient. The relationship between the coefficient of hydraulic conductivity and the temperature of the frozen soil was obtained experimentally.

4. Parameters of moisture transfer in the unfrozen part of freezing soils were investigated to establish the applicability of Darcy’s law. A relationship between Kp and dP/dx was developed for loam and kaolinite clay taking into account density and temperature. A method was proposed to consider the initial gradient in cryogenic moisture transfer in freezing soils in terms of its intensity.

Acknowledgments

The study was supported by the Russian Foundation for Basic Research, project no. 97-05-64961. Professor Peter Williams assisted in the translation of the text and Professor Antoni Lewkowicz helped with editorial changes.

References


