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PHYSICAL AND CHEMICAL PROCESSES IN FROZEN GROUND AND ICE

PHYSICAL MODELING OF FREEZING OF HEAVING SOIL. METHODS AND DEVICES

V.G. Cheverev[1,*], S.A. Polovkov[2], E.V. Safronov[1], A.S. Chernyatin[2]

[1] *Lomonosov Moscow State University, Department of Geocryology, Faculty of Geology, Leninskie Gory 1, Moscow, 119991 Russia*
[2] *Center for Monitoring and Geoinformation Systems of Pipeline Transport Facilities, Scientific Research Institute of Pipeline Transport (LLC Transneft Research Institute), Sevastopolsky prosp. 47a, Moscow, 117186 Russia*

**Corresponding author; e-mail: cheverev44@mail.ru*

We give the substantiation of the choice of methods and devices for laboratory modeling of the processes of freezing and heaving of soils in order to study their heaving properties and freezing parameters for verification of the developed mathematical methods of the process modeling. The methods under consideration make it possible to set and control in automated mode the dynamics of the temperature state, heat and water flows, heaving and shrinkage deformations, moisture content and bulk density, pore hydraulic pressure, and formation of segregation ice in freezing soils through the use of time-lapse video recording and the simulation of external mechanical and hydraulic loads.

Keywords: *physical modeling, methods, devices, freezing, soils, heaving, process parameters.*

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INTRODUCTION

Frost heaving of freezing soils is a dangerous geocryological process for buildings and engineering constructions in permafrost areas. Therefore, the prediction and control of this process are highly relevant.

Currently, despite many years of research into mechanisms and patterns of frost heaving and methods to reduce the negative impact of this process on the constructions, the heaving forecast problem is still far from a final solution. A number of mathematical formulas and equations of heat and mass transfer and deformations in freezing soils are proposed for semiempirical and numerical methods for predicting soil freezing and heaving of soils, which have not yet found experimental confirmation. The physical formulation of the problem for mathematical modeling of the freezing and heaving process needs significant development with due account for all the main factors of this complex process.

To verify the physical formulation of a numerical mathematical model of soil freezing and heaving, taking into account heat and mass transfer, ice formation, deformations of heaving and shrinkage, and pore pressure, the results of laboratory physical modeling are needed. To perform these laboratory experiments, appropriate methods and devices are needed.

In order to determine the methodologically important characteristics and parameters during the physical modeling of soil freezing, it is necessary to consider the mechanism of soil frost heaving.

The frost heaving deformations are caused by a set of heat and mass transfer, physicochemical and physico-mechanical processes depending on the properties of soils and external thermodynamic conditions.

The general frost heaving deformation consists of multidirectional deformations caused by segregation of ice, shrinkage and heaving, which can be expressed by the following equation [*Ershov, 2004*]:

$$H = h_f + h_{iw} - h_s, \quad (1)$$

where H is the resulting heaving deformation; h_f is the expansion deformation due to the water–ice phase transition in the soil; h_{iw} is the deformation of soil expansion due to freezing of water coming from the thawed zone to the frozen zone by cryogenic migration, including the flow of water through the thawed zone in transit from the underlying aquifer; h_s is the shrinkage deformation of the thawed zone due to outflow of water into the frozen zone in amounts exceeding the water content of the shrinkage limit.

Figure 1 presents the multi-layered dynamic structure of a freezing sample of finely dispersed soil. Frozen and thaw zones are distinguished in this structure. The frozen zone consists of the layers of the already frozen and freezing soils. In the thaw zone, a layer of transit moisture transfer and a layer with initial water content are distinguished. The freezing front (F_{fr}) marks the transition between the frozen and thawed zones.

A simplified scheme of freezing of the sample consisting of a frozen zone, an ice lens, a freezing zone, and a thawed zone is given in [*Gorelik, 2010, p. 51*]. The lens of ice grows on the border of the frozen and freezing zones. This is a specific case. A common case is when ice lenses appear and grow in the freezing zone simultaneously at different levels and with different intensities [*Cheverev, 2004*].

It follows from Fig. 1 that the method of physical modeling should include monitoring and measurement in time of deformation, mass-exchange and thermophysical parameters of processes, as well as boundary conditions for heat and mass exchange and external load. Let us consider this statement in more detail.

Deformation parameters. It follows from Eq. (1) that the heaving deformations in the frozen zone, shrinkage deformation in the thawed zone, and general frost heaving deformation of the soil along the height and width of the sample should be controlled in time. It is possible to calculate the time dependencies of moisture and soil density in height and width of the sample during freezing of a water-saturated soil sample, provided that these characteristics are determined as initial values before the experiment.

Thermophysical parameters. For physical modeling, it is necessary to control the temperature at the cold and warm ends of the sample, as well as to measure incoming and outcoming heat flows. In addition, it is necessary to monitor the movement of the freezing front in time.

Mass transfer parameters. During the physical modeling, it is necessary to determine the density of the water flow coming from the outside through the warm end of the sample and the distribution of pore pressure over the height of the melt zone over time. According to the temperature distribution in the frozen zone, it is possible to calculate the dynamics of pore pressure and its gradients. Taking into account the density of the moisture flow and the pore pressure gradient, the dependence of the soil moisture conductivity coefficient on temperature is calculated.

Cryogenic structure. To observe the formation of cryogenic structure in the soil on the lateral surface of the sample during its freezing, it is necessary to provide for the possibility of time-lapse video recording. Time-lapse videography is a special type of film and photography, in which a series of frames of the same object are photographed from the same shooting point at regular time intervals. It is intended for photographing slow processes.

Using special additional methods, it is necessary to determine temperature dependencies of the following soil characteristics: the coefficients of thermal conductivity and heat capacity in thawed and frozen zones, the unfrozen water content in the frozen zone, and the initial densities and water contents of the freezing soil.

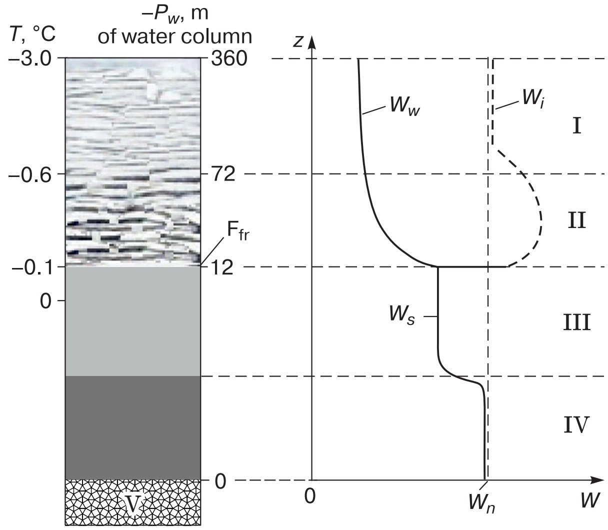

Fig. 1. A scheme of the characteristic zones and layers and parameters of freezing of silty clay soil.

I – frozen layer of the frozen zone; II – freezing layer of the frozen zone; III – layer of transit moisture transfer in the thawed zone; IV – layer of initial moisture in the thawed zone; V – capillary-water-saturated layer of sand. T – temperature (critical and characteristic values); P_w – pore hydraulic pressure; z – height; W_w, W_i, W_s, W_n – water contents corresponding to the unfrozen water, ice, shrinkage limit, and initial moisture, respectively; F_{fr} – freezing front.

On the side surface of the sample needle marks are installed using regular grid (10 × 10 mm) pattern to fix in time the layer-by-layer deformations of the freezing soil sample in height and width by videography.

This approach serves as the methodological basis for the selection of methods and devices to achieve the aim of the work – the physical modeling of soil freezing and heaving.

ANALYSIS OF EXISTING METHODS OF PHYSICAL MODELING

The heaving of freezing soils as a dangerous process for engineering constructions attracted the attention of Russian railway engineers at the end of the 19th century [*Shtuckenberg, 1894; Voislav, 1896*]. Since then, several hundred scientific papers have been published on the problem of frost heaving, which indicates both the significance of the process and its complexity.

The first simple experiment was carried out by S.G. Voislav in 1896. He experimentally established the heaving of the freezing soil placed in a bowl with water absorbed by the soil (Fig. 2).

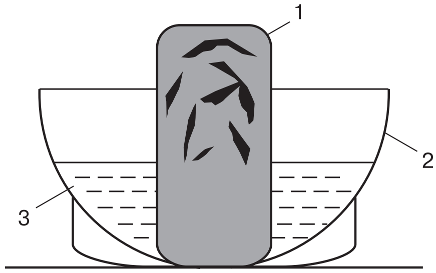

Fig. 2. Scheme of the experiment on freezing a soil sample in water [*Voislav, 1896*].

1 – soil; 2 – bowl; 3 – water.

Experimental investigation of the process of freezing and heaving of soils was carried out in more detail at the beginning of the 20th century (Fig. 3) [*Taber, 1930*]. A sample of clay for freezing was installed with a stamp in a sleeve with a porous bottom. The sample was frozen using a cryostat, the body of which had thermal insulation to ensure unilateral freezing of the sample. The sleeve with a porous bottom was installed in a container with water and sandy bed.

The experiments of S.G. Voislav and S. Taber were important for their time, but the potential of such devices is insufficient for modern physical modeling.

In studies of the mechanism of cryogenic migration and frost heaving performed up to 1990, the authors applied basically the same type of devices that provided for unilateral freezing of soil samples [*Bazhenova, Bakulin, 1957; Nersesova, 1961; Ananyan, 1970; Alekseev, 2020*].

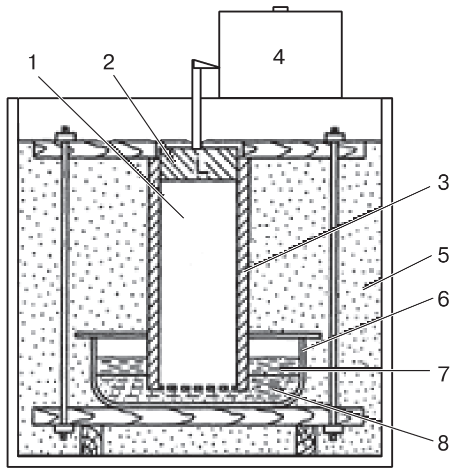

Fig. 3. A device for freezing a soil sample [*Taber, 1930*].

1 – clay sample, 2 – stamp, 3 – sleeve with a porous bottom, 4 – cryostat, 5 – thermal insulation, 6 – reservoir, 7 – water, 8 – sand with water.

V.Ya. Lapshin and L.B. Ganeles [*1979*] experimented with large (about 0.2, 1, and 3 m) samples and found that the maximum heaving of soils appears upon the freezing rate of about 1.5–2 cm per day. An example of the hardware implementation of the method of physical modeling of soil freezing is the device, the scheme of which is given in Fig. 4. The device was installed in the freezer and consisted of a cylindrical body with thermal insulation and a Plexiglas cylinder with soil samples. The cylinder with the sample was placed on a water-saturated fine-grained sand. A container with water was applied to the sand. Thus, the inflow of water from the outside was realized (an open mass transfer system).

The boundary temperature conditions were set by electric heaters using thermo-elements and heat exchangers. The pressure ring protected the cylinder from lifting due to the tangential forces of heaving of the soil. The general deformations of the frozen soil sample were measured by a clock-type deformation sensor. This device did not provide instruments for measuring pore hydraulic pressure, pore fluid flow density, and dynamics of temperature field.

A disadvantage of this device was also the absence of the possibility of observing the development of cryogenic structure, the advance of the freezing front, layer-by-layer deformations, and the intensity of the water flow into the sample.

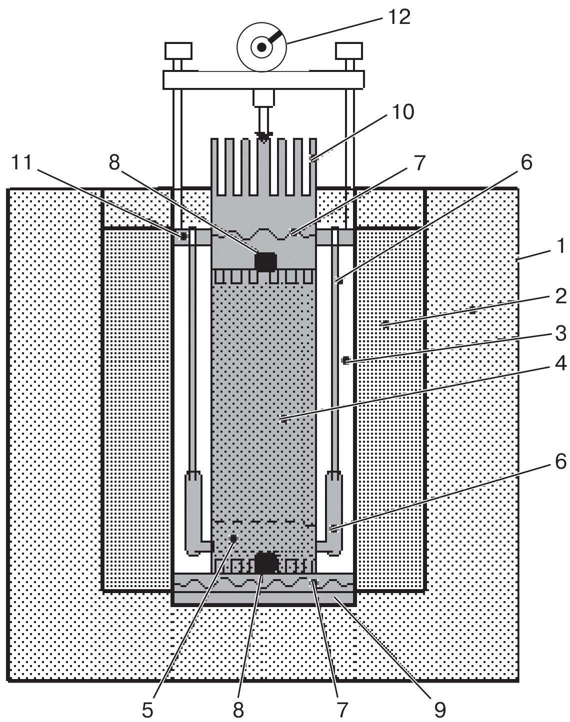

Fig. 4. Soil heaving meter [*Lapshin, Ganeles, 1979*].

1 – carcass, 2 – thermal insulation, 3 – Plexiglas cylinder, 4 – soil sample, 5 – fine sand, 6 – reservoir with water, 7 – electric heater, 8 – thermoelement, 9 – heat exchanger bottom, 10 – heat exchanger top, 11 – ring, 12 – strain sensor.

E.D. Ershov, V.G. Cheverev, and Yu.P. Lebedenko [*1988*] proposed a method and device for determining the hydraulic component of the pressure of frost heaving of soil by measuring the maximum pressure, at which cryogenic migration and heaving stop, with a dynamometer; this stop corresponds to stopping of the meniscus in the capillary tube (Fig. 5). The idea of this method was as follows. A sample of completely water-saturated soil was placed in a sleeve, at the bottom of which there was a layer of sand for water supply to the lower end of the sample. With the help of thermo-elements, constant temperatures were maintained at the ends of the sample.

A subzero temperature corresponding to the transition of the soil state from plastically frozen to hard-frozen is set at the upper end, and a positive temperature of about +0°C is maintained at the lower end of the sample. After temperature stabilization at the ends of the sample, the movement of the meniscus in the capillary tube is recorded in time, which allows calculating the amount of water entering the sample through unit area per unit time. During freezing, frozen and thawed zones separated by a freezing front appear in the sample. At the moment of the appearance of a frozen layer at the upper end of the sample, the screw is brought to the dynamometer. The value of the hydraulic component of the heaving pressure is determined by the dynamometer at the moment of stopping the flow of water into the sample through the lower end according to the meniscus stop; this ensures an important advantage in the possibilities of measurements.

It should be noted that with the stop of cryogenic migration under the action of the load, the freezing front does not stop and its progress causes a reverse outflow of the pore solution from the front. A similar device was subsequently implemented by V.G. Cheverev in the first normative document on laboratory determination of the degree of frost heaving of soils [*GOST 28622-1990, 1990*].

The closest technical solution for the purposes of physical modeling of soil freezing and heaving is a device, the schematic diagram of which is given in Fig. 6. Note the specific features of this device. In all cases, the external water source is located at the same level with the porous plate in the upper part of the chamber. An independent measurement of the full heaving is performed using a DC displacement sensor. Ten thermistors are mounted along the sample in contact with it.

Experiments with a freezer were carried out inside a room with a constant temperature close to the average temperature at the ends of the sample. The freezing of the sample was carried out from the bottom up, and the resistance to movement of the frozen part of the sample was reduced by using Teflon lubricant inside the chamber. A computer in combination with a multi-program unit made it possible to change the temperature at each end of the sample at a given rate.

The disadvantages of the device (Fig. 6) are: the lack of control over the layer-by-layer heaving of the freezing zone and shrinkage of the thawed zone of the

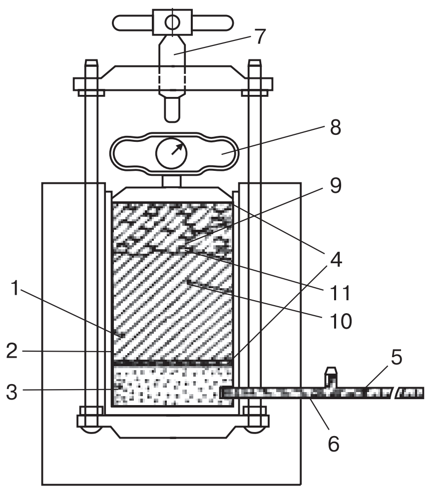

Fig. 5. Device for determining the pressure of frost heaving of soil [*Ershov et al., 1988*].

1 – soil sample, 2 – sample sleeve, 3 – capillary-saturated fine sand, 4 – thermoelements that do not interfere with the flow of water, 5 – meniscus; 6 – calibrated glass capillary, 7 – screw, 8 – dynamometer, 9 – frozen zone, 10 – thawed zone of the soil sample, 11 – freezing front.

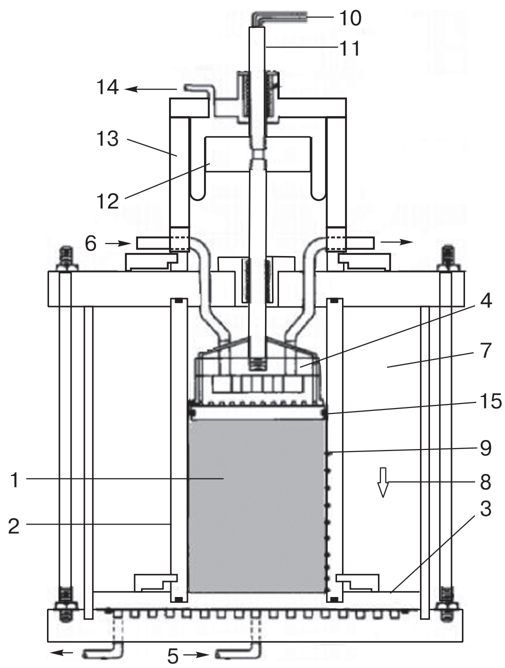

Fig. 6. Diagram of the freezer [*Penner, 1986*].

1 – soil sample, 2 – chamber (plastic pipe), 3 – cold stamp, 4 – warm stamp, 5 – cold antifreeze, 6 – warm antifreeze, 7 – thermal insulation, 8 – direction of heat flow in the sample, 9 – thermistors, 10 – a tube for supplying water to the sample, 11 – a tube for controlling the heaving deformation of the sample, 12 – piston,13 – cylinder, 14 – compressed air inlet, 15 – porous plate.

soil during its freezing, the lack of the means for measuring the pore pressure along the height of the thawed zone and the high-temperature frozen zone. Time-lapse video recording of ice segregation and measurement of the density of water flow into the sample from the outside are also not provided.

It was shown in [*Cheverev et al., 2013*] that the orientation of the sample, i.e., the change of the cryogenic migration vector to the gravity vector, does not significantly affect the final results, since the suction force of cryogenic migration is many times greater than the gravity force in soil samples of relatively small height. As a result, freezing of the soil from below under other equal conditions, as shown by comparative tests [*Cheverev et al., 2013*], does not affect the final result in determining the degree of frost heaving of the soil, but has a significant technological benefit, because only in this case a large-area cooling plate can be used in the device and several soil samples can be simultaneously placed on it for freezing at a given temperature.

Another positive effect is that when freezing from below, the frozen layer is immobile and heaving goes upward. This eliminates the problem of soil freezing from the inner surface of the sleeve and artificial containment of the heaving. It becomes possible to assess the influence of hard-to-control freezing forces in this process.

The boundary conditions for freezing a soil sample to determine the soil heaving capacity according to the standard procedure [*GOST 28622-2012, 2012*] assume cooling of one end to –4°C and heating of the other end to +1°C. The use of artificial heating does not allow us to freeze the sample completely, the freezing front slows down its movement and practically stops at the level of approximately 2/3 of the sample height. At the same time, favorable conditions arise for the intensive growth of a thick layer of ice at the freezing front (Fig. 7). As a result, the tested soil, in accordance with the provision of the standard [*GOST 28622-2012, 2012*], becomes excessively heaved, although initially it may not be.

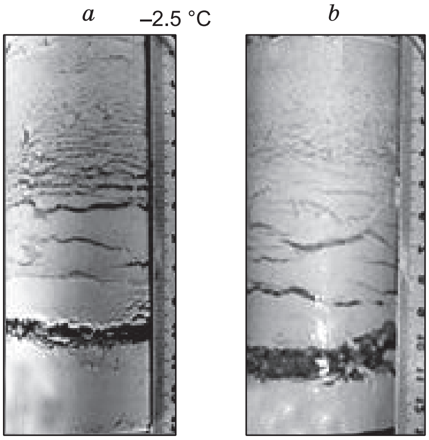

Fig. 7. Cryogenic structure of kaolinite silty clay frozen with boundary conditions of –2.5 and +0.5°C under loads:

a – 0.06 MPa; *b* – 0.04 MPa [*Cheverev et al., 2013*].

In the natural environment, the freezing of the seasonally thawed layer (STL) usually occurs in other thermal and physical conditions. In the autumn–winter period, the freezing of the STL comes from the soil surface and from the permafrost table. Between the two freezing fronts, a layer is formed, in which there is practically no temperature gradient, and the average temperature in this layer corresponds to the temperature of the beginning of soil freezing. This phenomenon was not taken into account in the standard procedure for measuring soil heaving [*GOST 28622-2012, 2012*].

To take into account this natural phenomenon under laboratory conditions, it is advisable to create a zone with zero temperature around the sleeve with the sample while eliminating local heating of the warm end of the sample. At the same time, the side wall of the sleeve must have sufficient thermal resistance to protect the temperature field of the freezing soil. For example, the wall thickness of a plexiglass sleeve of 15 mm, as experiments have shown, is sufficient.

It is also advisable to provide a method for determining the degree of heaving of a freezing soil sample with normal, increased, or decreased hydraulic pressure from the warm end of the sample. Without going into detail, such freezing options are dictated by the diversity of natural hydrogeological conditions; some of them are considered in [*Gorelik, 2010*].

Laboratory experiments are conducted and planned in order to accurately measure the movement of water through the thawed and freezing zones of the soil in dependence on the pore pressure gradient, temperature gradient, and chemical potential gradient in the frozen zone. Such carefully measured experimental data form the basis for determining, which mathematical model of the freezing process is correct and adequately reflects the physical essence of the heaving process.

METHODOLOGY OF THE PHYSICAL MODELING

The authors carried out laboratory physical modeling of one-sided freezing of soil samples with an influx of moisture from the outside under fixed boundary conditions for temperature. As tested model (reference) soil, a natural dusty, heaving clay of kaolinite composition was used. As a result of the research, the characteristics of the reference soil, the parameters of its freezing and heaving process were obtained under given boundary conditions for heat and mass transfer. These data were used in the future to verify the physical formulation of the mathematical model of freezing and heaving of soils, taking into account heat and mass transfer and shrinkage of the melt zone.

Devices for physical modeling

The instrumental base to carry out the investigations consisted of the following devices: (1) a meter of frost heaving of soils; (2) a cryothermostat (CTS); (3) a special mold for compacting the tested soil; (4) a universal meter (thermograms of freezing–thawing of soil and the unfrozen water content); (5) devices for determining hydraulic conductivity of fine-earth soils in the thawed state by the method of stationary moisture exchange; and (6) a thermal conductivity meter for the frozen soil by the method of stationary thermal regime; other auxiliary equipment.

The studied characteristics of the model soil are as follows: the dependence of its bulk density and water content at capillary moisture saturation on the load in the thawed state; the unfrozen water content (W_w) in the temperature range of 0 to –5°C; thermograms of freezing–thawing; thermal conductivity and heat capacity of the soil in the thawed and frozen states; effective heat capacity (taking into account the heat of phase transitions); the dependence of the moisture transfer coefficients on the temperature in the frozen and thawed state.

Methods for determining these characteristics and the results of their application are described in articles and monographs [*Cheverev, 2003a,b, 2004; Cheverev et al., 2021*].

The boundary conditions measured and controlled in time, the parameters of the soil freezing process and its characteristics are as follows: the boundary conditions of the freezing and heaving process, the dynamics of the temperature field and pore pressure [*Cheverev et al., 2021, Fig. 8*], the movement of the freezing front, the flow of cryogenic migration, layer-by-layer deformation of frost heaving of the freezing zone and shrinkage of the thawed zone, and video fixation of the cryogenic structure formation.

To achieve the research goal, an automated device was developed, the main distinguishing feature of which, giving a significant positive effect, was that the soil samples were frozen from the bottom up, and the water supply went from the top to the bottom. At the same time, an external load was applied from above from the side of the thawed zone (Fig. 8). The justification for the validity of the application of the proposed technique (we are talking about freezing from below) to determine the characteristics of the frost heaving of soils is given in [*Cheverev et al., 2013*], as well as in the description of the design of testing equipment (see below).

The device consists of a high-temperature freezer, in the internal volume of which a positive temperature of 0–0.1°C is maintained. At the bottom of the chamber, there is a cooling thermal plate with a cavity, in which the antifreeze of the cryothermostat circulates. Two supports are installed on the thermal plate performing the role of the power frame of the device together with the thermo-plate. A pipe (the square-section 70 × 70 mm and the height 150 mm) made of transparent acrylic glass with a metal bottom and with a vertical channel is installed on the thermal plate. The channel is filled with an aqueous salt solution, the freezing temperature of which corresponds to the temperature at the freezing front of the soil. This temperature is equated to the temperature of the beginning of freezing of the tested soil according to the results of preliminary determination.

In the lower part of the channel, a metal plug tightly adjacent to the thermal plate is installed, thanks to which, as established by experiment, the supercooling of the solution at the initial stage of freezing is reduced. The position of the freezing front in the soil sample in time is determined visually using time-lapse video, as well as the distribution of temperatures along the height of the sample using a set of temperature sensors.

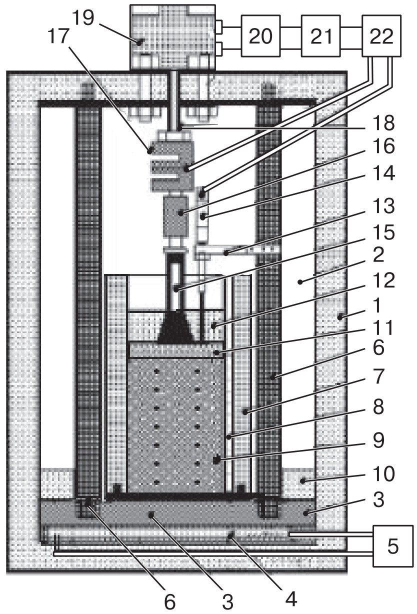

Fig. 8. A device for physical modeling of freezing and heaving of soil with control of boundary conditions and determination of the process parameters.

1 – high-temperature freezer, 2 – internal volume of the chamber to maintain a temperature of 0°C, 3 – thermal plate with a hollow, 4 – hollow, 5 – circulating liquid thermostat for freezing a soil sample, 6 – support racks, 7 – a sleeve for placing the tested soil sample, 8 – cylindrical channel filled with an aqueous solution, 9 – soil sample, 10 – thermal insulation ring, 11 – ceramic capillary-pore water-saturated plate, 12 – a layer of capillary saturated fine-grained sand, 13 – bracket, 14 – displacement sensor, 15 – support rack, 16 – coupling, 17 – force sensor, 18 – pneumatic cylinder rod, 19 – pneumatic cylinder, 20 – pneumatic actuator, 21 – air compressor, 22 – electronic control unit.

As a justification for the appropriateness of the load application from the thawed zone, we note the following. Since the force of action is equal to the force of counteraction, it is possible to apply a load and measure the heaving force from both the frozen and thawed zones, which in this case is equivalent. This condition is ensured by the fact that the ceramic porous plate must have sufficient strength against destruction when a load is applied and, at the same time, maintain a hydraulic conductivity of no less than the hydraulic conductivity of the soil of the thawed zone. The area of the plate should be as close as possible to the area of the soil sample, ensuring free sliding along the sleeve. The size of the base area of the support post should be smaller, which is necessary for the free movement of water into the freezing soil sample from the sand layer through the porous plate.

With this variant of physical modeling, the area on which the load acts is equal to the area of the frozen soil surface, taking into account the correction for the friction force of the soil in the thawed and freezing zones on the surface of the sleeve. The results obtained will be applicable in practice if the area of the heaving soil is equal to the area of the construction basement. However, if the area of the heaving soil is larger than the area of the basement, then the effect of normal heaving forces on the foundation increases proportionally to this difference.

Methods of physical modeling

The device described above allows testing under the following moisture conditions.

The first mode is a closed system without water supply from the outside. In this case, a waterproof film is placed between the sand layer and the soil.

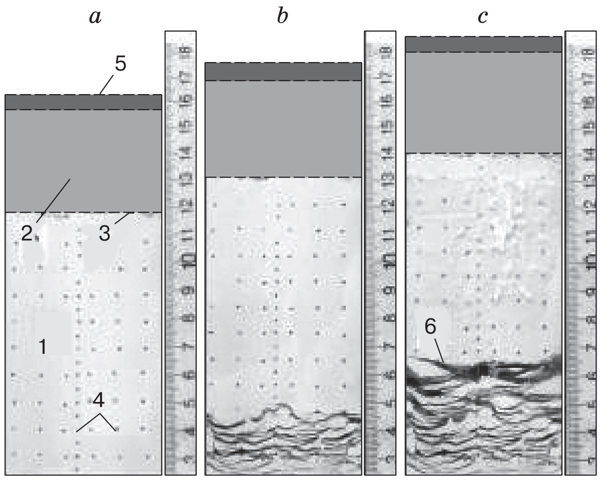

Fig. 9. Results of freezing of a sample of kaolinite clay (experiments without load).

a – before the experiment (0 h); *b*, *c* – during the experiment (*b* – 23 h; *c* – 63 h); 1 – soil sample; 2 – capillary-saturated fine-grained sand; 3 – the boundary between sand and clay; 4 – position sensors; 5 – metal plate with drainage holes; 6 – ice lenses.

The second mode is an open system, in which the flow of water from the outside takes place, but without pressure. In this case, the sand layer is moistened only up to the state of capillary saturation. Capillary water in the sand pores is a reserve for the flow of water from outside into the freezing ground. By varying the thickness of the sand layer, you can control the volume of the reserve water. At the same time, there is no hydrostatic pressure from the capillary-saturated fine-grained sand on the tested soil, since the water is in a capillary-suspended state. The water layer in the 3-cm-thick sand layer, taking into account its porosity, is 1 cm. This amount of water that has entered the freezing water-saturated soil during cryogenic migration and segregation of ice lenses will be sufficient for the soil to manifest a relative deformation of frost heaving of more than 0.1 f.u., if the initial height of the soil sample is 10 cm. In this case, the soil is assessed as excessively heaving. With an increase in the height of the tested soil sample, for example up to 15 cm, the thickness of the capillary-saturated sand layer should be proportionally increased to 4.5 cm.

The third mode is an open system, in which the flow of water from outside into the frozen soil sample occurs under pressure. In this case, a layer of water is maintained above the layer of water-saturated sand, the level of which relative to the surface of the soil sample determines the pressure.

The creation of various modes of water flow into the soil in this technical implementation allows us to study the dependences of the characteristics of heaving on various hydrogeological conditions of the soil freezing.

The design of the device also provides for the possibility of creating static pressure on the sample due to the existing pneumatic actuator. In the course of physical modeling, only the second mode has been used so far: an open system for water exchange at atmospheric pressure level.

Before the start of freezing, the temperature of the samples should be lowered to 0–0.1°C. For this purpose, the corresponding temperature is set in the cooling thermostat. The hollow plate is cooled to the specified temperature by pumping the thermostat antifreeze in a closed circle and thereby cools the tested soil samples. Thermal insulation of the freezer is efficient enough to exclude a significant influx of heat from outside. Precooling of the samples of the soil as a whole is completed after reaching a temperature of 0–0.1°C in the upper part of the chamber. This stage lasts for several hours.

The thermostat is switched to the freezing temperature of the soil (for example, –2.5°C), and the circulation of antifreeze is switched on. The plate acquiring a subzero temperature cools the lower layers of the soil sample that become frozen when their temperature reaches the freezing point and below. In this case, there is a freezing front separating the formed frozen and the overlying not yet frozen (thawed) soil layer. Control over the advance of the freezing front in time and depth is carried out using a cylindrical channel (Fig. 8).

During the freezing of the heaving soil, the pore solution moves from the unfrozen zone to the freezing zone, where excess water freezes with the formation of ice lenses and soil heaving. During the freezing of a soil sample, its layer-by-layer heaving deformation is fixed with a help of a grid of position sensors by time-lapse video recording. Deformations are fixed in both vertical and horizontal directions. Zero deformations in the horizontal direction can occur when the soil reaches the shrinkage limit in the measured layer. At the same time, the pneumatic drive system works to maintain static pressure on the freezing soil sample, which is heaving, exerting back pressure on the force sensor and the rod of the pneumatic cylinder.

As an example, the results of freezing of the sample of kaolinite powdery clay obtained during the time-lapse survey tests at the time before the experiment (0 h) and after 23 and 63 h of freezing are shown in Fig. 9.

In this experiment, the soil sample in the form of a parallelepiped with transverse dimensions of 70 × 70 mm and the initial height of 120 mm was placed in a 15-mm-thick acrylic glass cage. The capillary-saturated sand was placed on top of the sample; in turn, on top of the sand, a metal stamp with holes was installed. Needle-type position sensors were used.

Figure 9 demonstrates that, due to the freezing from below, cryogenic structure of the wavy-layered horizontal type is formed in the soil After 63 h of freezing, the size of the ice lenses increased significantly to 3–5 mm, and the rate of freezing and heaving naturally decreased. The total heaving deformation (including heaving of the frozen and shrinkage of the thawed zones) of the clay sample upon its incomplete freezing reached 24 mm.

CONCLUSIONS

1. A brief analytical review of developments in the field of laboratory (physical) modeling of the heaving process during soil freezing, which, according to the authors is given. A comparison of the methods and devices simulating the heaving process in two significantly different ways is performed: freezing from above with water inflow from below and freezing from below with water inflow from above. It is shown that the second method has a number of advantages. Thus, it eliminates the influence of the freezing forces of the soil with the inner surface of the sleeve, allows one to increase the number of simultaneously tested samples, maintains the temperature conditions of laboratory modeling close to those under natural conditions of the seasonally freezing layer, and creates new opportunities for studying the freezing process taking into account changes in hydrogeological factors.

2. A structurally optimal set of methods is proposed for determining the characteristics and parameters of the heaving process. This set ensures measuring of a full set of physical characteristics of the freezing and heaving processes and the corresponding external conditions and yields promise for its further use for verification of existing and developed mathematical models of soil freezing and heaving.

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References

Alekseev A.G., 2020. Laboratory studies of the pressure of cryogenic heaving of soils. *Vestnik NITs Stroitel'stvo,* No. 3, 5–12 (in Russian).

Ananyan A.A., 1970. Water in rocks, its migration during freezing. In: *Bound Water in Dispersed Systems,* Moscow, Izd. Mosk. Gos. Univ., Iss. 1, p. 146–154 (in Russian).

Bazhenova A.P., Bakulin F.G., 1957. Experimental studies of the mechanisms of moisture movement in freezing soils. In: *Materials on Laboratory Studies of Frozen Ground*, Moscow, Izd. Akad. Nauk SSSR, No. 3, p. 117–123 (in Russian).

Cheverev V.G., 2003a. Classification of water bonding forms in the frozen fine-grained soils. *Kriosfera Zemli* VII (3), 31–40 (in Russian).

Cheverev V.G., 2003b. Properties of bound water in cryogenic soils (analytic review). *Kriosfera Zemli* VII (2), 30–41 (in Russian).

Cheverev V.G., 2004. The Nature of Cryogenic Properties of Soils. Moscow, Nauchnyi mir, 234 p. (in Russian).

Cheverev V.G., Burnaev R.S., Gagarin V.E., Safronov E.V., 2013. Influence of external pressure on the degree of frost heaving of clay soils. *Kriosfera Zemli* XVII (4), 57–62 (in Russian).

Cheverev V.G., Safronov E.V., Korotkov A.A., Chernyatin A.S., 2021. Physical statement of the problem for a numerical model of soil freezing and heaving taking into account heat and mass transfer. *Nauki Tekhnolog. Truboprovodn. Transp. Nefti Nefteproduktov,* **11** (3), 244–256 (in Russian).

Ershov E.D. (Ed.), 2004. Methods of Geocryological Research: A Textbook. Moscow, Izd. Mosk. Gos. Univ., 512 p. (in Russian).

Ershov E.D., Cheverev V.G., Lebedenko Yu.P., 1988. *Method for Determining the Pressure of Frost Heaving of Soil: Patent No. 1596241*, Byull. 36, Publ. Sept. 30, 1990.

Gorelik Ya.B., 2010. On the calculation methods of the engineering construction displacements caused by heaving of freezing layer. *Kriosfera Zemli* XIV (1), 50–62 (in Russian).

GOST 28622-1990, 1990. Soils. The Method of Laboratory Determination of the Degree of Heaving. Moscow, Standartinform, 12 p. (in Russian).

GOST 28622-2012, 2012. Soils. The Method of Laboratory Determination of the Degree of Heaving. Moscow, Standartinform, 12 p. (in Russian).

Lapshin V.Ya., Ganeles L.B., 1979. Recommendations for Determining the Frost Heaving of Soils of the Bases of Buildings and Structures. Sverdlovsk, Ural Politekhnich. Inst., 34 p. (in Russian).

Nersesova Z.A., 1961. Influence of exchange cations on water migration and soil heaving during freezing. In: *Research on the Physics and Mechanics of Frozen Soils*. Moscow, Izd. Akad. Nauk SSSR, Iss. 4, 251 p. (in Russian).

Penner E., 1986. Aspects of ice lens growth in soils. *Cold Reg. Sci. Technol.* **13**, 91–100.

Shtukenberg V.I., 1894. On the heaving control fight against the depths on the railways. *Zh. Ministerstva Putei Soobshcheniya* (Moscow), book 2, p. 24–30 (in Russian).

Taber S., 1930. The mechanics of frost heaving. *J. Geology* **38** (4), 303–313.

Voislav S.G., 1896. A brief description of the causes of heaving of the Nikolaev railway. *Tr. Byuro Issled. Pochvy* (Proceedings of the Bureau of Soil Research). St. Petersburg, 133 p. (in Russian).

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