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FUNDAMENTAL ISSUES OF EARTH'S CRYOSPHERE

ANALYSIS OF CONCEPTS ON THE MECHANISM OF CRYOGENIC MIGRATION OF WATER IN FREEZING GROUND

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A retrospective analysis of the results of studies of the mechanism of water migration in freezing soils was carried out on the basis of an analysis of about 160 scientific publications by Russian and 100 foreign authors. For the analysis, articles, monographs, dissertations, patents, conference proceedings and scientific reports were used. The main ones are given in the list of references. Special attention is paid to the key aspects of the formation of understanding of the driving forces of cryogenic migration (moisture transfer) in freezing soils. This analysis is necessary for the correct physical formulation of the mathematical model of the process of frost heaving of soils.

Keywords: *analytical review, mechanism of cryogenic migration, frost heaving of soils.*

INTRODUCTION

Frost heaving of soils is widespread in the area of seasonal and long-term freezing in the cold regions of the Earth and is a dangerous criogenic process for buildings and constructions. For this reason, the study of the physical nature of heaving and the development of mathematical models adequate to the physical essence of the process, methods of its prediction and management is an urgent scientific and practical problem.

In general, the mechanism of frost heaving of soils is a complex interaction and interdependence of heat transfer, mass transfer, phase transitions of water in the pores of the soil, segregation of ice and the dynamics of its stress-strain state. Heat transfer as the root cause ensures the removal of phase transition heat, capacitive and convective heat from the freezing soil. By freezing the soil, the heat transfer initiates mass transfer and segregation of ice in soils prone to frost heaving.

The dynamics of the stress-strain state of the freezing soil depends on three factors. Firstly, on the expansion of water in the pores of the frozen zone of the soil during its transition to ice *in situ* with the appearance in cramped conditions of significant solidification forces at small deformations of heaving. Secondly, due to the significant inflow of water from the melt layer of the soil into the freezing one via cryogenic migration, during freezing, this gives the main contribution to the heaving of the soil. Thirdly, the outflow of water from the melt zone into the freezing one lowers the pore pressure in it, causing shrinkage, which reduces the overall deformation of the frost heaving of the soil.

Heat transfer and cryogenic migration, in turn, are accompanied by segregation ice-separation in the form of a special layered cryogenic structure, which leads to anisotropy of the building properties of frozen soils and significant draft of the constructions during the thawing.

The analysis of the state of the study of these processes is directly related to the physical formulation of the problem of mathematical prediction of freezing and heaving of soils, taking into account the processes of heat and mass transfer, segregation of ice, deformation and forces of heaving of soils. The results of theoretical and experimental studies obtained by specialists of Lomonosov Moscow State University and The Transneft Research Institute on the problem of frosty soil heaving is a test numerical mathematical model. The presentation of these results are distributed over a number of articles. This paper briefly summarizes only the ideas about the mechanism of cryogenic migration and frost heaving of soils that are of paramount importance for the development of a mathematical model.

DRIVING FORCE OF CRYOGENIC MIGRATION

A very significant number of works have been devoted to the development of ideas about the nature of migration processes in freezing dispersed soils and their frost heaving, there are already several hundreds of them. In the last 10–20 years, a number of other articles have appeared, but they mainly have applied character. The analysis of published works is available in a number of review articles, dissertation chapters and monographs [*Sumgin, 1929; Beskow,* *1935; Edlefsen, Anderson, 1943; Goldstein, 1948; Bazhenova, Bakulin, 1957; Orlov, 1962; Tsytovich, 1973; Brovka, 1991; Black, 1995; Cheverev et al.,1998; Cheverev, 2003a, 2004*].

Nevertheless, due to the appearance of new theoretical and experimental results, including those belonging to the authors of the article, new generalizations become relevant. This allows us to hope for a significant development of the existing ideas about the heaving process and the solution of the problems of creating an adequate mathematical modeling of the freezing process of fine-grained soils in terms of physical formulation and taking into account heat and mass transfer, heaving, shrinkage and segregation of ice.

Back at the end of the XIX century, the need to find out the cause of frost heaving of soils and on this basis, new developments of means of protecting engineering structures from this dangerous process became acute in connection with the construction of roads in the districts of the Siberia and the Russian Far East. The researchers noted a significant increase in the water content (ice content) of the freezing soil and its heaving. So, G.Ya. Bliznin in his work gave data on an increase in water content in the upper horizons of the soil in winter. He suggested the possibility of transferring pore water in freezing soils *under the influence of thermal gradient*, which was logically based on general considerations [*Bliznin, 1890*].

In the works of our predecessors several basic theories (hypotheses) have been suggested for the clarification of the formation of the driving forces of the cryogenic migration of water and the frost heaving of soils. These theories include *capillary (meniscus) force, head pressure, compressional compaction, crystallization of water, the forces of surface adsorption, vacuum, potential double electric layer (osmosis), gradient of the thermodynamic potential*. All of them will be discussed below.

Capillary forces. The works of Russian engineers-trackmen V.I. Shtukenberg [*1894*] and S.G. Voislav [*Cvigunov, 2018*] should be attributed to the first studies of the physical essence of the process of frost heaving of soils. They laid the basic theoretical prerequisites for studying the physical essence of the processes of heaving and migration of water in freezing soils.

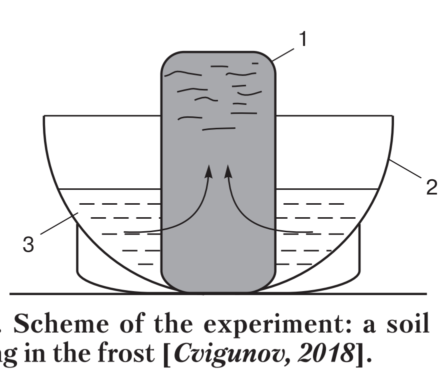

Fig. 1. Scheme of the experiment: a soil sample freezing in the frost [*Cvigunov, 2018*].

1 – soil sample; 2 – bowl; 3 – water.

In Fig. 1, there is a diagram of a simple experiment of S.G. Voislav, from which it follows that a sample of thawed soil placed in the frost in a bowl with water, froze with an increase in volume and the formation of ice layers. At the same time, the amount of water in the bowl decreased proportionally. As a result of the experiment, the author came to the conclusion that the deformations of the frost heaving of soils were caused by the absorption of water from the thawed layer of soil into the freezing one and the formation of ice layers from this water.

V.I. Shtukenberg put forward a physical explanation of the causes of soil heaving in the ground embankment of the railway track *by the influence of water migration in the liquid phase from the lower to the upper freezing layers* of the ground embankment. He also proposed an approximate mathematical description of the process of soil heaving. *Capillary hypothesis* of V.I. Shtukenberg [*1894*] was one of the first hypotheses of water migration during freezing and heaving of soils.

In 1929 and 1930, S. Teber carried out a series of laboratory experiments on freezing samples of kaolinite clay and obtained the results that became classic. Most authors have referred to these experimental works up to the present time. In Fig. 2 it is shown, as

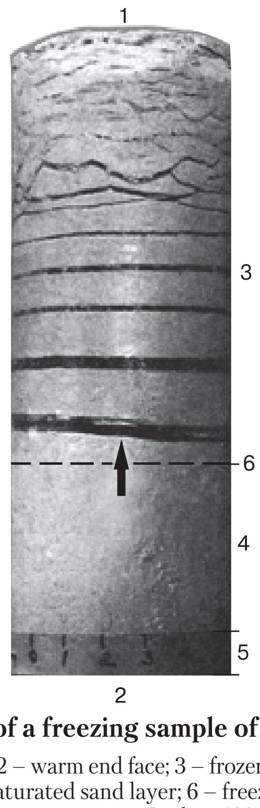

Fig. 2. Photo of a freezing sample of kaolinite clay.

1 – cold end face; 2 – warm end face; 3 – frozen layer; 4 – thawed layer; 5 – water-saturated sand layer; 6 – freezing front; *arrow* – direction of cryogenic migration [*Taber, 1930*].

a clear example, the result of the formation of cryostructure in a freezing kaolinite clay sample with water inflow from the outside, from the side of the warm end face of the sample. As can be seen in Fig. 2, a horizontal-wavy micro-lenticular cryostructure had firstly formed from the cold end face of the sample, and then gradually, under the influence of a decrease in the freezing rate, it has been becoming the lanticular and the sparser one. S. Teber also proposed a probable mechanism for the growth of ice lens in freezing soil based *on capillary suction* [*Taber, 1930*].

The capillary hypothesis has not been further confirmed. The facts of the occurrence of capillary meniscuses during the crystallization of water in the soil have not been obtained subsequently. The soils with full water saturation are devoid of menisci due to the absence of a water–air phase boundary. At the same time, it is known that fully water-saturated soils are the heaviest ones. Moreover, the definition "the capillary mechanism of frost heaving", as will be revealed below, ignores the undeniable surface and osmotic forces involved in the formation of heaving.

At the same time, this does not mean that capillaries in the soil do not play a significant role in frost heaving. On the contrary, they are the medium in which the pore solution transits from the thawed to the freezing zone of the soil under the action of a pore pressure gradient initiated by the negative thermal gradient of the freezing zone [*Beskow, 1935*].

Pressure forces. The assumption of the water transfer under the action of "pressure forces" arising due to an increase in the specific volume of water during its transition to ice was developed in [*Nikiforov, 1912; Dranitsyn, 1914; Sumgin, 1929*]. According to the "theory of pressure migration", the water transfer in the pores of the freezing soil takes place under the influence of pressure occurring during the freezing of water (which leaks down along a weakly permeable horizon) or during the freezing of a layer closed between the underlying frozen stratum and the layer of winter freezing. Further studies have revealed that the theory of pressure forces explains quite well the formation of injection frost mounds (pingo) and therefore is a special case of non-segregation heaving.

Compression compaction. V.O. Orlov [*1962*] assumed the presence of a compressional compaction process of the thawed layer of the freezing soil due to pressure from the weight of the overlying frozen layer, considering this to be the cause of the flow of pore water from the thawed into the freezing layer. However, this hypothesis has not been supported by experimental data. The thawed layer is compacted by the negative pore pressure occurring due to the outflow of water into the freezing layer.

Under certain conditions, the pressure of the frozen layer or of the load from the construction on the thawed layer of the freezing soil affects its heaving, but this is a second-level factor, and it is not the root cause of cryogenic migration and heaving. On the contrary, in the conditions of an open mass transfer system the significant external load, as a rule, complicates the penetration of cryogenic migration into the freezing layer and at critical pressure stops it completely. Without a load on the freezing soil in its thawing zone, a negative pore pressure ($-P_w$) is formed due to the outflow of pore solution into the freezing zone. Pressure is measured on a relative scale, where the atmospheric pressure is taken as zero, and the compression pressure is taken as positive ($+P_w$).

The formation of segregation layers of ice, in general, is not associated with the pressure forces of the pore solution. But there may be a special case when under the unconsolidated compaction the thawed layer undergoes an external load. As a result, the negative pore pressure decreases towards neutral and can even turn into positive one, thereby accelerating the cryogenic migration and increasing the heaving of the freezing soil. This fact was first established experimentally and published in the work [*Cheverev et al., 2013*].

The forces of water crystallization. Along with the capillary theory, S. Teber proposed a *theory of cryogenic migration due to the forces of ice crystallization*, which, like the capillary hypothesis, proved untenable. By the forces of crystallization, he assumed the ability of ice crystals to attract water from the underlying horizons. S. Teber wrote: "The growing ice crystal is enveloped by a thin film of water similar to adsorbed water formed on many other solids coming into contact with water. When a molecule in the film moves in the direction of the ice crystal and joins it, it is replaced by another water molecule, as a result the integrity of the film is preserved" [*Taber, 1930*].

In the course of further researches the validity of the theory of ice crystallization forces has not been confirmed. Experiments carried out by the authors of [*Bazhenova, Bakulin, 1957*] have demonstrated that the hydrophobization of the mineral component of the soil, which eliminates the meniscal forces, stops its heaving due to cryogenic migration – although the phase transition of water into ice occurs in the pores of the soil, but the water freezes in place. At the same time, the reverse process – the squeezing of water from the freezing front – is possible and is realized at the favorable combination of the freezing rate and resistance to the flow of the pore solution from the front of the freezing into the thawed zone.

Surface adsorption forces. Influenced by the works of S. Teber, G. Beskow put forward *the theory of adsorption forces of the mineral component of the soil* [*Beskow, 1935*]. In this theory, for the first time, the idea was expressed that the film migration to the front of freezing is associated with freezing of the outer part of water films adsorbed by the mineral particles and soil aggregates. As for the effect on film water, G. Beskow considered the crystallization process of this part of the water to be similar to the evaporation process.

Here it is appropriate to recall the results of the study of water transfer in unfrozen soils from the work [*Lebedev, 1919*].

The decrease of the amount of water molecules in the film due to its gradual crystallization contributes to the corresponding release of part of the surface energy of the mineral component of the soil, which causes and supports the migration of water to the freezing front. At the same time, A.F. Lebedev has rightly believed that the capillary water in the thawed zone is a source of loss of film water in the frozen zone, and the capillaries themselves are the ways of migration.

The theory of adsorption forces of the mineral component of the soil was the right direction in the development of ideas about the mechanism of cryogenic migration and heaving of soils, but not its completion. For example, this theory has not yet explained why sand are not heaving as clay and silt, although their hydraulic conductivity is higher by orders of magnitude; also, the role of a double electric layer on mineral particles in this process has not been considered.

Thus, this theory has needed further development in terms of taking into account the physicochemical nature of the adsorption of water and ions on a solid mineral surface.

Vacuum. V.E. Borozinets and G.M. Feldman have proposed a vacuum filtration mechanism for the formation of thick ice lens. They consider that the growth of thick ice lenses occurs with periodic temperature fluctuations on the surface of the earth, which initiates the reciprocating movement of the freezing front in the soil at a certain depth. In the freezing cycle, the ice formation produces the soil heaving, and in the thawing cycle, the internal volume of the soil decreases. As a result of thawing, the local volumes with low pressure are formed, into which the water rushes from the lower zone of the soil. Further, this additional volume of water freezes, increasing the thickness of the ice layer, and so a thick layer of ice grows [*Borozinets, Feldman, 1981*]. In fact, the authors have suggested a mechanism for the formation of the driving force of cryogenic migration during cyclic freezing-thawing at the local level due to the fluctuations in the internal pore hydraulic pressure.

The existence of such a mechanism when the temperature fluctuates on the surface of the soil causes doubts since the reciprocating process, which is considered by the authors, is reversible (defrosting is changed by freezing), and the decrease in pressure during the thawing is replaced by its increase during freezing, therefore, the inflow is replaced by the outflow in the same volume, other things being equal.

However, the fact of the formation of the increased iciness and the thick ice lens has been established in the top of permafrost, and there is another explanation for this fact. It has been experimentally established that during the gradual thawing of frozen soil the conditions for ice segregation are preserved in its frozen layer. The accumulated ice is preserved during the subsequent freezing, and its growth resumes in the next thawing-freezing cycle [*Ershov et al., 1976*].

The potential of a double electric layer on the surface of mineral particles (osmosis). Theoretical and experimental studies have proved that the leading role in the mechanism of cryogenic migration and heaving of freezing soils is played by a double electric layer (DEL) of ions in the water environment on the surface of the mineral clay particles, as well as the existence of a diffuse ion layer in DEL.

M.N. Goldstein, L. Cass and R.D. Miller have suggested to evaluate the role of the basic properties of DEL on the surface of mineral particles in cryogenic migration [*Goldstein, 1948; Cass, Miller, 1959*].

The theory of DEL has been developed since the middle of XIX century regardless of the frost heaving of soils. It made it possible to explain such interesting physical-chemical effects and phenomena as electroosmosis, electrophoresis, direct and reverse osmosis, properties of colloidal systems, etc. [*Shchukin et al., 2004*].

This theory is based on the concept of the German physicist Otto Stern (1924). In this theory he has combined the theory of Helmholtz–Perrin (1878) and the Gouy–Chapman (1910) (Fig. 3). According to these ideas, at the boundary of the contacting phases on solid hydrophilic surface there are the atoms of the crystal lattice with uncompensated charges, the so-called layer of potential-determining ions (PDI), and the electrostatically adjacent layer of

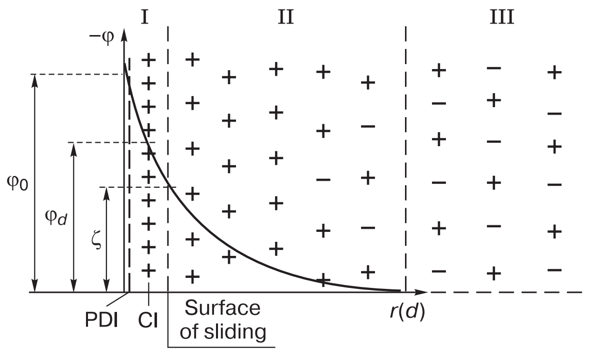

Fig. 3. The electric double layer (by Stern) and the potential change in it (φ):

I – adsorption layer; II – diffuse layer; III – volume solution; PDI – layer of potential-determining ions of mineral surface; CI – a layer of counter ions; φ_0 – thermodynamic adsorption potential; φ_d – diffusion potential, ζ – electrokinetic potential of diffuse layer of ions on the surface of sliding; $r(d)$ – radius (thickness).

counterion (CI) from aqueous solution. The layer of counterions consists of two parts. One part is directly adjacent to the interfacial surface and forms an adsorption layer (Helmholtz layer) with a thickness equal to the diameter of the hydrated ions that make it up. The other part of the CI DEL is located at a certain distance and is called the diffuse layer of counterions (Gouy layer). With increasing distance, the gravity of the counterions to the PDI layer decreases, the concentration of counterions gradually decreases from the maximum value to the average concentration in a neutral solution. At the same time, the ratio of the OC ions (that are in direct proximity to the PDI) to the diffuse layer ions on average constitutes 95:5 % of the total amount, respectively.

An electric field operates within the DEL, the intensity of which is characterized by a certain value of the potential. In Fig. 3 several types of the changes in the DEL potential with the increase of the distance from the surface are demonstrated.

– The thermodynamic potential of the surface (φ_0) is a complete potential jump between the mineral surface and any point in the deepness of the solution where the influence of the surface does not affect.

– The potential of the diffuse layer (φ_d) is the potential arising at the boundary between the adsorption and diffuse layers. In the adsorption layer, the DEL-potential decreases linearly.

– Electrokinetic potential on the sliding surface, or ζ-potential. This potential arises under the action of external forces on the sliding surface. It is maximal at the outer boundary of the adsorption layer and decreases exponentially along with moving into the diffuse layer.

There is reason to believe that the ζ-potential determines the maximum value of the cryogenic migration potential, so let's consider its properties in more details.

The value of the ζ-potential is affected by the thickness of the diffuse layer. The smaller the thickness the lower is the ζ-potential, up to the zero value (when the cryogenic migration stops). In turn, the thickness of the diffuse layer is influenced by various factors. Thus, with the change of concentration of the external solution (which is not included in the DEL) its equilibrium with the diffuse layer is disturbed, because they compete for a coupling with water molecules. In the case of extreme compression, the diffuse layer degenerates and its ions pass into the adsorption layer. Consequently, the effect of compression of the diffuse layer with an increase in soil salinity leads to the cessation of cryogenic migration and heaving. Figure 4 shows the dependence of the cryogenic migration flow on the concentration of the pore solution of the freezing silt clay. When it is increased to 1 N (N is the normality of the solution, it denotes the number of gram equivalents of this substance in one liter of solution or the number of milligram equivalents in one milliliter of solution) the cryogenic migration stops, which indicates the ultimate compression of the diffuse ion layer.

However, at the solution concentration of 0.01 N, the migration flow is maximal, since the ζ-potential of the diffuse layer of ions (at their optimal content) is maximal. At the same time, in ultra-fresh clay (the normal concentration (C) is approximately equal to 0 N), the migration flow is only half of the maximum, which is explained by a significant decrease in the thickness and the ζ-potential of the diffuse layer due to its erosion in the ultra-fresh state. At that, a certain amount of exchange ions is always present in the diffuse layer, as the water is the very good solvent.

It should be taken into account that the ζ-potential of the diffuse layer is not a constant value and depends on the radius, the valence and the charge of the ions, as well as on the chemical nature of the solid phase surface, the temperature, the composition and the concentration of ions of the competing bulk solution.

The leading role of DEL in the formation of frost heaving of the soil can be defined as the existence of a semi-permeable soil layer, which initiates the flow of cryogenic migration from a warm zone to a cold one during freezing, where water freezes in the plastically frozen zone of the freezing soil as thermodynamically excessive and causes deformations and heaving forces. Here, obviously, one can find an analogy with the method of measuring osmotic pressure with a semi-permeable membrane.

The ion-molecular theory of the double electric layer (developed in the field of physical chemistry) can be used to predict and control the frost heaving of freezing soils at a qualitative level. The object for this is the ζ-potential of the diffuse ion layer. Since the diffuse ion layer accumulates the main volume of

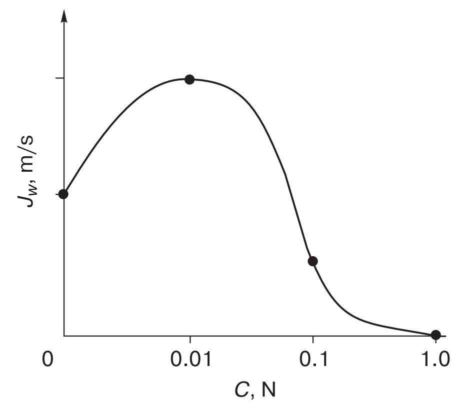

Fig. 4. The character of the effect of the normal concentration (C) of a pore solution of sodium chloride of freezing silty clay on the flow rate of cryogenic water migration (J_w) [*Cheverev, 2004, p. 138*].

bound water (up to 95 % DEL), then it is possible to control the frost heaving by acting on its ζ-potential (Fig. 3). For example, a change in the chemical composition and concentration of the pore solution changes the value of the ζ-potential and the thickness of the diffuse ion layer. This, in turn, affects the intensity of cryogenic migration and the frost heaving of the freezing soil.

Due to the complexity of the clay soil (polymin-erality, polydispersity, heteroporocity, multiphase), the quantitative forecast of frost heaving based on the theory of DEL is not yet seemed possible.

At the same time, the phenomenological model formulated at the macroscopic level can be successfully constructed for frost-sensitive soils and will allow a reliable quantitative forecast. Therefore, the main efforts in the development of numerical modeling of the freezing and heaving of soils forecast are currently aimed at using the basics of thermo-dynamics of irreversible processes and phenomenological laws.

Thermodynamic potential of water in the soil. It is known that the water in the soil obeys the general trend and flows from places with higher potential energy to places with lower potential energy, which is also valid for freezing of heaving soil.

The method based on the use of partial, or free, specific energy of J.V. Gibbs (*the chemical potential of water*) is used to assess the energy state of water in soils, Since the chemical potential characterizes the state of the component in the absence of external force fields, and the water in the soil is yet under their influence, then the chemical potential of water in the soil has received the special name *thermodynamic potential of water* [*Thermodynamics..., 1966*].

Chemical potentials of water in the SI system are represented in the dimension of work – kJ/kg (or J/mol). However, for the convenience of a quantitative description of the water transfer process in freezing, thawing and frozen soils, it can be represented in the dimension of the equivalent pressure – Pa (or kg/cm^2, atm, more convenient in *meters of water column*, 1 m of water = 10^4 Pa). Based on equality $-\mu_w$ [kJ/kg] = $-P_w/\rho_w$ [m^3·kg/(m^2·10^3 kg)], where ρ_w is the density of water, expressing weight in terms of mass ($F = mg$), we get [m^3·kg·m/(m^2·10^3 kg·s^2)]. Taking into account the fact that kJ = m^2·kg (mass)/s^2, we come back to the dimension [kJ/kg] with a coefficient of 0.981, i.e. 1 MPa = 0.981 kJ/kg [*Cheverev, 2004*].

At the same time, the pressure in the pore solution formed by external energy impact (hydrostatic pressure, suction, compression, etc.), in contrast to the equivalent pressure, is considered simply pore pressure and is denoted $-P_w$. The negative pore pressure in cryogenic soils is not measured in vacuum units, as it is customary in atmospheric physics (from 0 to 1 atm). It is measured in the scale adopted in agrophysics, when the normal atmospheric pressure in pure volumetric water (which is outside the influence of the soil) is equated to zero as neutral.

Hydrostatic and compression-filtration pressures in the soil have positive values ($+P_w$), and the suction pressure and all the components of the chemical potential, when converted to equivalent pressure, have negative values ($-P_w$).

Thus, when studying the energy state of water and the driving forces of water transfer in cryogenic soils , it is necessary to differentiate between the chemical potential of water (μ_w), directly determined by the hydrophilic ability of the soil, and the potential of water as a function of the process itself and external conditions.

When a part of water freezes, the amount of liquid phase decreases, and the remaining part of it is under lower pressure (or higher binding energy) compared to free water. Hence $dP_w/dT < 0$. At the same time, ice crystals having no hydraulic connection with water are free from the pressure existing in the liquid phase. The pressure acting on the crystals no longer depends on T, and, consequently, $dP_i/dT = 0$.

Considering this, we use the Clapeyron–Clausius thermodynamic equation for one-component two-phase ice–water system, which has the form

$$dP/dT = L/(T_0(V_2 - V_1)), \qquad (1)$$

where L is the specific heat of the phase transition from the first phase to the second one; $(V_2 - V_1)$ – the difference of specific volume of phases; T_0 is the temperature of the water phase transition at atmospheric pressure on the Kelvin scale.

Modified equation (1) for conditions of water energetic state in soils by N.E. Edlefsen and A.B.C. Anderson, takes the form [*Thermodynamics..., 1966; Cheverev, 2003b*]:

$$dP_w = DT/(T_0 V_w), \qquad (2)$$

where V_w is the specific volume of the liquid phase of water.

The validity of using such an approach to frozen and freezing soil was experimentally and analytically confirmed by V.G. Cheverev and co-authors. After substituting the values of T_0, and L and V_w (as for free water, which is acceptable) we get that an increase in pressure on liquid water by 0.1 MPa leads to an increase in the freezing temperature by 0.0824 K. At that, the expression [*Cheverev et al., 1998; Cheverev, 2003a,b*] is true:

$$dP_w/dT = -1.2 \text{ MPa/K} = 120 \text{ m of water/K}. \qquad (3)$$

Hence, according to S.N. Buldovich and V.G. Cheverev, the equation for calculating the density of the flow of unfrozen water in frozen siol (I_{wm})

under the action of a thermal gradient (dT/dz) has the form [*Ershov, 1999*]

$$I_{wm} = -\lambda_{wm}(T)kDT/dz, \qquad (4)$$

where $\lambda_{wm}(T)$ is the coefficient of water conductivity of the frozen soil, which significantly depends on the type of soil and its temperature, m/s; k is the proportionality coefficient, m of water column, equal to 120 m/K; z is the height of the frozen zone, m.

The thermal gradient in the freezing zone of the soil (more precisely at the freezing front) initiates the gradient of hydraulic pore pressure and water flow in the thaw zone (I_{wt}), for which, the following equation is valid according to S.N. Buldovich and V.G. Cheverev [*Ershov, 1999*]:

$$I_{wt} = -\lambda_{wt}k(T_{bf} - T_{\xi})/(l - \xi), \qquad (5)$$

where λ_{wt} – coefficient of hydraulic conductivity of the unfrozen soil, which depends considerably on the type of soil, its density and water content, m/s; k – coefficient of proportionality, m of water column, equal to 120 m/K; T_{bf} – the freezing point of soil in the thawed zone (static characteristic); T_{ξ} is the temperature at the freezing front, depending on the type of soil and the dynamics of its freezing (dynamic characteristic): it decreases with an increase of the freezing rate and becomes equal to T_{tot} when the freezing front, cryogenic migration and heaving stop.

Equations (4) and (5), presented in potential form, are the basic ones for the development of a mathematical model of freezing and heaving of soil considering mass transfer.

CONCLUSIONS

Basing on the analytical review of a large volume of theoretical, model and experimental studies, the authors came to conclusions important for the development of the theory of cryogenic migration and frost heaving of soils. In the future, it is possible to improve the physical formulation of the mathematical model of the process of freezing and heaving of soils, taking into account heat and mass transfer.

In general, the process of frost heaving of freezing soil can be attributed to a new chapter of the scientific direction of physical-chemical mechanics of materials and colloidal systems, the founder of this system is academician P.A. Rebinder. The mechanism of cryogenic migration and frost heaving of soils is a complex interaction and interdependence of heat transfer, mass transfer, phase transitions of water in the pores of the soil, segregation of ice and the multidirectional dynamics of its stress-strain state. Heat transfer as the root cause ensures the removal of heat of phase transitions, of the capacitive and convective heat from the soil. By freezing the soil, heat transfer initiates mass transfer and ice segregation in heaving soils.

The article provides an overview of the development of ideas about the root cause of cryogenic migration of water in freezing soils and its driving forces, based on which the following conclusions are made.

1. The possibility of transferring pore water in freezing soils under the influence of a thermal gradient was first proposed by G.Ya. Bliznin [*1890*]. Attempts to find another explanation, independent of the thermal gradient, were unsuccessful.

2. V.I. Shtukenberg [*1894*] and S. Taber [*Taber, 1930*] proposed the capillary hypothesis as the first cause of water migration during freezing and heaving of the soil. However, this hypothesis has not been confirmed. The driving force of cryogenic migration occurs in the freezing zone of the soil, where the menisci of pore water do not form at the border with air, which is practically absent in heaving and water-saturated soils. However, the capillaries of the soil perform an important transit function for cryogenic migration.

3. The theories of pressure forces and compressive compaction of the soil have also not been confirmed, since as a result of the outflow of water from the thaw zone into the freezing zone, the negative pore pressure with shrinkage of the soil is formed under the front of the freezing, but not a positive one as it takes place during the compression compaction.

4. The theory of the forces of water crystallization during its transition to the ice phase has also not been confirmed. The main role of the adsorption forces of the mineral component was confirmed by the experiments of A.P. Bazhenova and F.G. Bakulina in 1957 on hydrophobization of the soil mineral matrix, after which the cryogenic migration and heaving stopped [*Bazhenova, Bakulina, 1957*].

5. The theory of the main role of surface adsorption forces of the mineral component of the soil in the process of cryogenic migration (put forward for thawed soils by A.F. Lebedev, and for frozen soils by G. Beskow) turned out to be significantly closer to the truth than the hypotheses considered above. The decrease of water molecules in the film due to its gradual crystallization contributes to the release of part of the surface energy of the mineral component of the soil, which causes and inhibits the migration of water to the freezing front. The theory of adsorption forces was the right direction, but this direction was far from completion. For the development of this theory it was necessary to take into account the physical chemistry of surface phenomena, namely, the double electric layer of ions according to Stern.

6. M.N. Goldstein [*1948*], L.C. Kass and R.D. Miller [*Cass, Miller, 1959*] assigned an essential role in cryogenic migration to osmotic properties of the diffusion of a double electric layer. More developed version of this theory is proposed in this article.

Due to the particular complexity of the composition of heaving (and, as a rule, clay) soils, the microscopic level of knowledge of the mechanism of cryogenic filtration does not imply in the foreseeable future the development of a numerical mathematical model of freezing of heaving soils on this basis. Therefore, in order to achieve a real practical result, it is necessary to move to the macroscopic, phenomenological level of development of the theory of frost heaving of soils. To achieve this goal, it is necessary to use the concept of thermodynamic potential of water.

7. The theory of cryogenic migration flow formation based on thermodynamic potential uses a modified equation Clapeyron–Clausius, thermodynamically substantiated by N.E. Edlefsen and A.B.C. Anderson [*Edlefsen, Anderson, 1943*] and experimentally and analytically confirmed and proved by V.G. Cheverev [*Cheverev, 1998, 2003a*].

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