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MASS TRANSFER IN FROZEN SOILS

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SYNOPSIS The results of investigation into the processes of mass transfer in frozen soils under the effect of different driving forces are reported. The data presented explain the mechanism and relationships between moisture transfer and segregated ice formation in frozen soils in a gradient temperature field under the effect of salt solution concentration gradient, mechanical loads, compression, and injection. The data available today on moisture transfer in the field of electric stresses have also been generalized and presented. A quantitative evaluation of migration flow density values and other thermodynamic parameters was made. Changes in the texture and structure of frozen soils due to unfrozen moisture migration are discussed. Based on the experimental data and other materials, a comprehensive analysis has been carried out to identify common features and differences in the processes of mass transfer in frozen soils under the impact of various driving forces. The results obtained are of great significance both for general and engineering geocryology.

Moisture transfer and ice accumulation in frozen soils constitute one of the most important problems of general and engineering geocryology, physico-chemistry and mechanics of frozen soils. Successful solution of both the scientific problems concerned with the transformation of the composition, cryogenic texture and properties of frozen soils and those of engineering geocryology responsible for the stability of buildings and structures erected on them depends on the extent of cognition of the above-outlined processes. This necessitates studying a great number of complicated chemical, physical and physico-mechanical processes occurring in frozen soils under the impact of different thermodynamic fields. Insufficient knowledge of the problem, its great scientific and practical importance predetermine the actuality of the present studies.

The authors have conducted experimental studies to identify the mechanism and laws of moisture transfer and ice accumulation in frozen soils under the influence of different driving forces. To solve the tasks, the procedures of experimental studies of the processes of moisture transfer and ice formation in frozen soils under the impact of mechanical stresses and osmotic forces have been worked out.

In the course of the experiments, frozen soils of disturbed structure were used: monomineral clays of the Paleogene: kaolinite (eF_2) and montmorillonite (ef_1O gl) of eluvial genesis; and polymineral clay (mF_2kv) of marine genesis to investigate the influence of mineral composition. The effect of particle-size distribution was studied on loam (aIII) and loamy sand (gmII) from the Quaternary and glacial-marine sediments of West Siberia, and the sands of marine genesis (mI_3).

It is known that unfrozen water films in frozen soils are located in the field of action of the adsorption forces of the surface of mineral particles. Their properties and, first and foremost, mobility are determined by the surface energy of these particles, as well as chemical and mineral composition, fineness and temperature of soils. Therefore, studies of the processes of physico-chemical interaction between mineral particles and soil moisture, phase transfer of water and conditions of its thermodynamic equilibrium are deemed to be important. The perturbation of general thermodynamic equilibrium is possible when frozen soils are affected by temperature, electric, magnetic and gravitational fields, mechanical forces and hydrostatic pressure, and due to chemical interaction between the soil and chemically active environment. Such effects on frozen soils lead to the changes in temperature, pressure, concentration, and mobility of water films, and to the formation of moisture potential gradients.

The experimental studies (Yershov, 1979) showed that the presence of temperature and electric fields in frozen soils results in moisture migration and segregated ice formation. The migration of moisture in the gradient temperature field is conditioned primarily by the processes of diffusion and thermodiffusion. The diffusional transfer of water results from its nonuniform freezing in the gradient temperature field, and formation of unfrozen water-content gradients. A decrease in ground temperature disturbs the thermodynamic equilibrium between the unfrozen water films and ice. The freezing out of a part of water and the attainment of a new equilibrium bring about thinning of water films and reduction of the unfrozen water thermodynamic potential in the region of lower negative temperatures. In the region of higher negative temperatures, the water films are thicker, they are more mobile, and, naturally, the thermodynamic potential values are higher. A difference in water mobility causes its migration from the regions of higher mobility to the ones of lesser mobility, i.e. from high to low temperatures.

When studying the laws of moisture migration in the soils of different composition, texture and properties, it has been shown that the greatest redistribution of moisture is observed in clays, the first place among which belongs to the clay of kaolinite composition. It is associated with great values of moisture diffusion coefficients in kaolinite clays having thicker unfrozen water films. In montmorillonite clays, the unfrozen water films are less mobile. The clays of polymineral hydromicaceous-montmorillonite composition take an intermediate position between the kaolinite and montmorillonite ones. The densities of moisture migration fluxes decrease when transferring from clays to loams and loamy sands because the amount of unfrozen water decreases in coarser soils. In addition, the pore space structure in coarser moisture-saturated frozen soils is such that continuous water films are not formed in them on fairly long ways of moisture transfer. The moisture migration flux density in frozen loams decreases by two-three times, as compared to clays, that reduces segregated ice accumulation in the former. The region of segregated ice interlayer formation in finer soils is shifted to the side of higher negative temperatures. With the temperature gradient build-up there occurs an increase in the density of the moisture migration flux, and in the intensity of moisture redistribution and segregated ice formation.

The studies of the process of moisture migration and segregated ice formation in frozen soils under the effect of temperature gradient have shown that its presence causes water films flow from the region of high to the region of lower negative temperatures; the moisture migration flux density being of the order of 10^{-7} gr/cm^2 . s.

Moisture migration in frozen soils under the impact of the electric field gradient has been studied less thouroughly. Contrary to moisture migration under the effect of the temperature gradient, its transfer in the field of electrical forces is conditioned by the electric potential gradient changing the total thermodynamic potential of soil moisture. The electric tension gradient in frozen soils causes migration of the unfrozen water films from the positively charged electrode - anode to the negative one - cathode. Creation of the electric field disturbs the equilibrium. The external electric field affects primarily the electric double layer in water films and changes the total thermodynamic potential of film moisture and ions of the dissolved salts. The formation of the thermodynamic potential gradient of moisture between the anode and cathode causes moisture migration in that direction and increases the total moisture content of soil in the region of the cathode. Moisture migration from the anode results in the thinning of water films there and in disturbing the thermodynamic equilibrium between the unfrozen water and ice. It leads to melting of the pore ice and recuperation of the thickness of water films. Nearby the cathode, on the contrary, the inflowing moisture increases the thickness of water films and disturbs the thermodynamic equilibrium, A surplus moisture freezes up while changing to pore and segregated ice.

It is obvious, that water migration in frozen soils in the gradient electric field depends on their composition and properties. Besides, in coarser soils the coefficient of moisture diffusion diminishes thus conditioning a decrease in density of the moisture migration fluxes from the anode to the cathode. Therefore, the smallest migration fluxes in the field of electric forces are in frozen sands and loamy sands which, practically, do not contain the most mobile loosely-bound water, whereas the biggest moisture fluxes are in kaolinite clays wherein unfrozen water films are very thick. In frozen montmorillonite clays characterized by small values of moisture diffusion coefficients, the moisture flux in the field of electric forces is also insignificant.

The studies of moisture migration in frozen soils interacting with water solutions of salt have shown that simultaneously with ion diffusion from the water solution (or salted ice) a liquid phase is also transferred to a sample. The main reason of such a transfer of salts lies in the presence of ion concentration gradient in the water solution and nonsaline soil. This gradient is directed from the water solution deep down the frozen soil causing transfer of ions in the same direction. The liquid phase migration in the same direction is conditioned by both the transfer of water films hydrated by ions, and, perhaps, by the difference in the total thermodynamic potential of moisture between the water solution and bound groundwater. Thus, when frozen soils in the process of slinization, contact water solutions or salted ice, there occurs an undirectional transfer of the salt ions and unfrozen water films.

Investigations into specific features of moisture migration in frozen soils under the effect of osmotic forces have shown that maximum densities of moisture migration fluxes are observed on the contact of saline soils with fresh ice (10^{-7} gr/cm^2. s) (or nonsaline soils with water solutions of salts) due to the presence of strong driving forces of moisture migration. A decrease in the moisture migration flux density with the distance from the contact cross-section is conditioned by a corresponding decrease in the gradients of the dissolved ions concentration and driving forces. The interaction of frozen soils with water solutions of salts results in a considerable moisture accumulation due to an intensive transfer of the liquid phase. The freezing of a portion of migrating moisture gives rise to the formation of segregated ice interlayers and streaky cryogenic structure, which causes strong volumetric heaving of frozen soils in the process of their salinization.

In has been shown that moisture transfer process also occurs when the liquid phase is influenced by the hydrostatic pressure. The main parameters which influence the process of injected ice formation are: pressure in soil moisture, ultimate shear strength of the unfrozen water films, and ultimately-long and instantaneous strength of the frozen soils. The injected moisture flow density, the seepage coefficient and the amount of ice accumulation increase with an increase in the fineness of soil particles and in the content of the kaolinite group minerals: the former reaches the values $6\ 10^{-5}$ gr/cm^2· s to $3\ 10^{-4}$ gr/cm^2· s. The value of initial hydrostatic pressure, under which the process of moisture injection begins, decreases with an increase in the fineness of soil particles and the growth of content of the kaolinite group minerals. Soil temperature decline increases the initial hydrostatic pressure needed for moisture injection and decreases the density of moisture injection flow and ice formation.

As has been demonstrated experimentally, soil deformation at the stage of long-term creep causes the flow of water films into the region of shear thus increasing the moisture and ice content therein and forming segregation micro- and macrointerlayers. It is known that due to the shear of thawed rocks, a change in the pore pressure and the moisture migration to the shear zone occur in the region of displacement. In contrast to the unfrozen soils, the pore space of frozen ones is filled with ice, therefore, only thin water films of bound moisture can be found in the field of mineral particle action. A decrease in the potential of bound water when it is influenced by shearing forces is caused by the tensile stresses between soil particles in the plane of shear. The action of shearing forces in frozen soils results in the formation of the total thermodynamic moisture potential gradient causing the transfer of the unfrozen water films into the region of shear. An increase in the water film thickness disturbs the thermodynamic equilibrium between the liquid phase and ice and leads to the freezing out of the excess unfrozen water. As a result, the total moisture and ice content increases and segregated ice interlayers are formed in the zone of shear. In the regions remote from the shear zone, the thinning of unfrozen water films also disturbs the thermodynamic equilibrium and causes pore ice melting. The total moisture content in these regions decreases.

It has been shown that the development of the migration process is significantly determined by the acting load and velocity of deformation, which is, probably, associated with different values of stress gradients.

A predominantly mixed migration-seepage mechanism is in operation when frozen soils are acted upon by press tools of different size and shape, because alongside with the formation of the microshear regions at an angle to a press tool plane, the compaction regions are also formed directly beneath the press tool. As a result, the moisture transfer in the shear zones occurs mainly due to the above-described mechanism, whereas the unfrozen water films are transferred to the regions of the compacted nucleus due to pressure, i.e. moisture is suezed out from the nucleus being compacted. The experiments proved that configuration of the zones of ice accumulation and dehydration depends on a press tool shape.

The maximum moisture accumulation in the shear region is observed in clay as compared to loam and loamy sand. The determination of the density of moisture migration flows to the shear zone in frozen soils of different fineness of particles has shown that their values considerably increase on the transition from sands to clays and reach $1\ 3\ 10^{-7}$ gr/cm^2· s. This is conditioned primarily by a high content of the liquid phase in clays and their high water conductivity in the frozen state. The influence of mineral composition on the processes of moisture transfer and ice accumulation is especially great in clays. Maximum values of moisture accumulation in the shear zone and dehydration of remote sections are observed in kaolinite clays and minimum values - in montmorillonite ones, the polymineral clay occupies an intermediate position.

The impact of soil density on the processes of moisture transfer and ice accumulation has been studied on the samples of kaolinite clay. As a result, it was established that an increase in soil density, other things being equal, entails a decrease in the density of moisture migration flows to the shear zone, and moisture accumulation therein (Fig.1), which is associated with smaller velocities of deformation of compacted clays. The intensity of moisture trans-

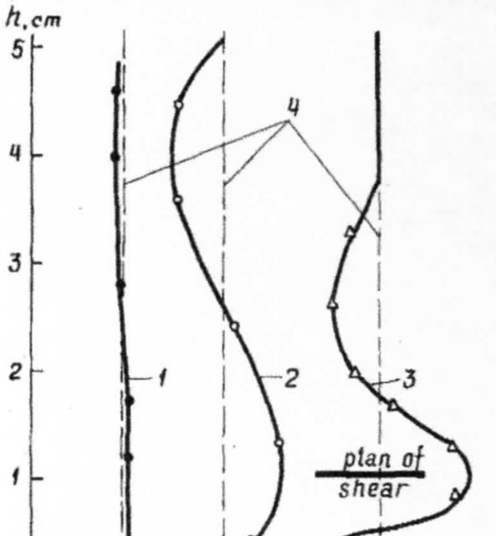

Fig.1 Redistribution of moisture in the samples of frozen kaolinite clay with various initial moisture content due to shear

1 - W_{in} = 29% ρ_d = 1.47 g/cm^3
2 - W_{in} = 39% ρ_d = 1.23 g/cm^3
3 - W_{in} = 52.2% ρ_d = 1.08 g/cm^3
4 - average moisture content

fer and ice accumulation in the shear zone was shown to decrease with a negative temperature decline. This happens due to a decrease in the content of the unfrozen water capable of micrating, and owing to a simultaneous decrease of the moisture transfer coefficients.

The main reason of moisture transfer under the effect of frozen soil compression lies in the presence of pressure gradients in the unfrozen water films. The pressure difference is responsible for the moisture movement to the periphery of samples under compression. At the same time, application of load to the frozen soil results in the thermodynamic equilibrium disturbance and melting of pore ice. The maximum unfrozen water seepage has been established in the clays with a high content of liquid phase. The intensity of seepage decreases with an increase in the size of soil particles from clays to sands, and maximum values of dessication of the frozen grounds under compression have been recorded in frozen clay samples. A decrease in the intensity of the unfrozen water seepage in the row from clay to loamy sands is associated, in considerable measure, with worsening of their moisture-conducting properties in this series. As has been established earlier, moisture diffusion coefficients decrease with an increase in the size of soil particles. It is due to this phenomenon that the intensity of unfrozen water seepage drops in coarser-grained soils. It has also been established experimentally, that the intensity of unfrozen water seepage depends on the load applied. With increasing load the seepage intensity increases as well. Thus, an increase of the load applied to a frozen clay from $3 \frac{kg}{cm^2}$ to $12 \frac{kg}{cm^2}$ caused a decrease in its moisture content by 20-25% on the average.

The impact of temperature on moisture seepage under compressional compaction is, as described above, analogous to that of temperature gradient in frozen soils. The intensity of water seepage in frozen soils drops with a decrease in temperature.

The studies conducted and the data available on the moisture transfer in frozen soils permitted a camparative analysis of this process occurrence under the effect of different driving forces with the aim of identifying its common and distinguishing features. The comparison showed that irrespective of different character and nature of impacts upon the frozen soil, common features of moisture transfer and ice formation process were revealed, namely: disturbance of thermodynamic equilibrium between liquid and solid phases of water and formation of gradients of driving forces. The redistribution of moisture and ice, i.e. dehydration of some of the soil zones and ice accumulation in the other have been noted. This leads to the transformation of the cryogenic texture of soils (Fig.2).

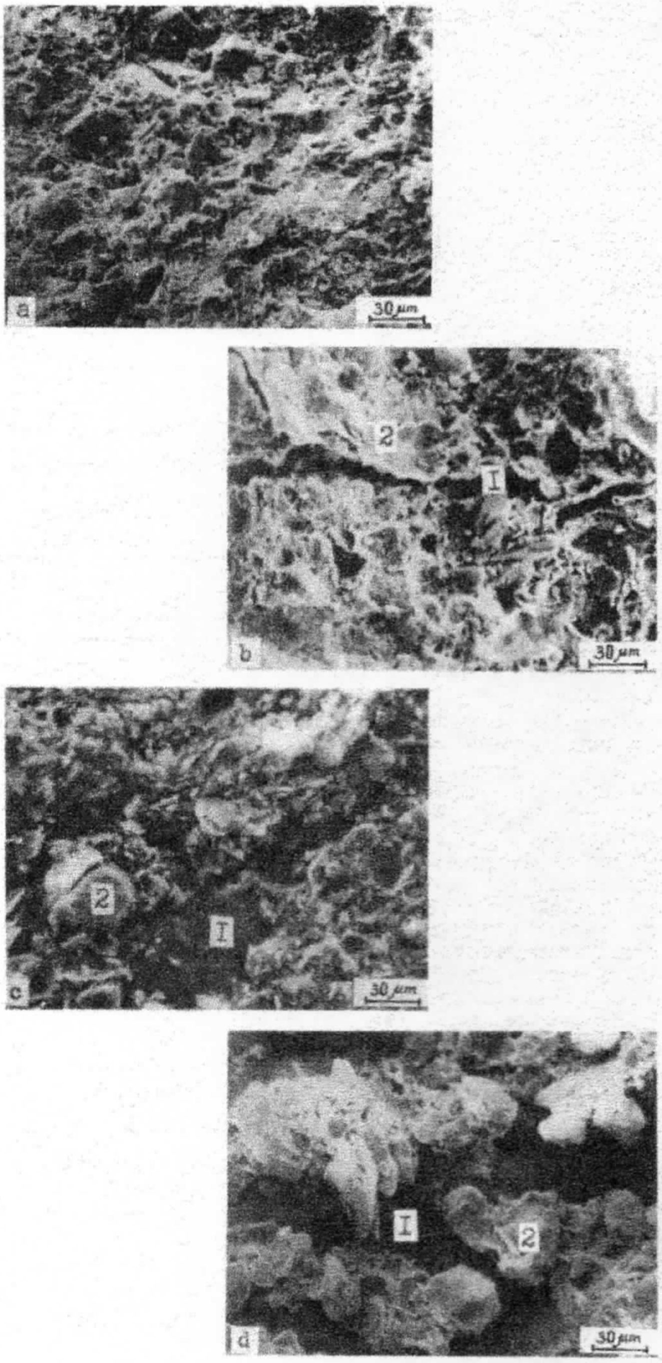

Fig.2 The patterns of ice formation in frozen soils under the impact of different driving forces of moisture transfer: a - original state of soil; b,c, and d - under the impact of gradients of hydrostatic pressure, temperature and osmotic forces, respectively; 1 - ice; 2 - mineral skeleton.

However, depending on the kind of impact on frozen soils, the moisture transfer and ice formation are characterized by their specific features. External effects, depending on the mechanism caused by them, can be subdivided into three groups. The first group comprises such effects on frozen soils which lead mainly to the migration of the unfrozen water films. The second group includes external effects on frozen soils that cause seepage of the unfrozen water films. And, finally, the third group includes external effects triggering off a combined migration-seepage mechanism of moisture transfer (Table 1). According to the different moisture transfer mechanisms, the processes of ice formation can be grouped into segregated, injected, and combined segregated-injected ice-forming ones. An analysis of moisture accumulation, depending on the mechanism of moisture migration and ice formation, has shown that maximum moisture accumulation is associated with the seepage-injection mechanism (average values of water flows I_w reach $10^{-4} - 10^{-5}$ gr/cm$^2 \cdot$ s), and the smallest - with the migration-seepage mechanism ($I_w = 10^{-7} - 10^{-8}$ gr/cm$^2 \cdot$ s).

TABLE 1

The Main Mechanisms and Driving Forces of Moisture Transfer in Frozen Soils

Mechanism of moisture transfer and ice formation	Main driving forces of moisture transfer	Main kinds of external effects on frozen soils
Migration - segregation	Gradient of osmotic forces	Interaction of soils with water solutions of salts; and saline frozen soils with fresh ice
	Temperature gradient	Temperature field
	Gradient of electric potential	Electric field
Seepage-injection	Gradient of hydrostatic pressure	Hydrostatic pressure
Combined migration-seepage mechanism of moisture transfer and segregated-injected ice formation	Gradient (driving forces of migration and seepage)	Different kinds of external mechanical impacts on frozen soils (shear, compaction, extention, compression).

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