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Deformations and strains in grounds subjected to freezing out and thawing

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Abstract

On the basis of the elaborated procedure for physical simulation of heat-mass exchange, physico-chemical, mechanical, texture- and structure-forming processes a study has been conducted of heaving, shrinkage, swelling, freezing out and other processes that make congelitation inevitable. It has been established that heaving occurs not only in freezing out but also in water-saturated dispersion rocks subjected to thawing as minus temperature values decrease as well as in salinity-affected frozen grounds. Numerical data have been obtained on the values of migratory water flows, intensity of segregation ice accretion, heaving, settling, shrinkage and swelling. Regularities have been established that govern the strain in the freezing out, thawing and frozen grounds, depending on their dispersion, chemico-mineral and chemical composition of the ambient water fluid, on moisture and density, the freezing and thawing regimes, external pressure and salinity.

When frozen rocks are subjected to salinization in a static temperature field, the rocks undergo heaving.
In a general form, the value of ground heave can be represented as follows:

$$ h_h = h_{h-o} + h_{j_w} - h_s, $$

where $h_{h-o}$ - ground heave-out due to a 9% volumetric increase of pore moisture during freezing (a heave caused by massive heave-out), cm; $h_{j_w}$ - ground heave due to moisture migrating into the frozen zone, cm; $h_s$ - shrinkage of thawed ground due to dehydration, cm.

Calculated value of ground heave due to moisture migration is equal to:

$$ h_{j_w} = I_{0.9} \cdot K_{an} \cdot K_w \cdot \Phi \cdot \text{grad } \tilde{\tau}, $$
where $\lambda_{an}$ – anisotropy factor, taking into account the schlieric slope; $K_w$ – moisture diffusion factor, cm$^2$/s; $\phi_t$ - thermogradiant coefficient, $\text{I/grad}$; $\tilde{t}$ - freezing-out time, $\text{s}$.

However, ground heave may also be due to massive heave-out. The heave value as attributed to by a 9% volumetric increase of the pore fluid during freezing can be expressed as follows:

$$ h_{n-o} = 0.09 \left( \frac{W_{w}}{W_{uf}} \right) \xi, $$

where $W_{w}$ - moisture of mineral seams of the ground, numerically equivalent to the moisture across the phase boundary, $\text{pp}$ of a unit; $W_{uf}$ - quantity of unfrozen water, $\text{pp}$ of a unit; $\xi$ - the freezing depth, $\text{cm}$.

Opposite in sign to ground heave is shrinkage, produced in the thawing part of the ground (below the freezing front) due to dehydration as well as to various physicochemical processes going on in the grounds: aggregation, coagulation, etc. Ground shrinkage value can be calculated using this expression:

$$ h_s = K_s \cdot \beta \cdot \Delta W \cdot \xi, $$

where $K_s$ – shrinkage anisotropy factor, showing the vertical shrinkage component of the ground; $\beta$ - coefficient of volumetric relative shrinkage of the ground; $\Delta W = W - W_{uf}$ - difference between initial moisture and freezing front moisture; $\xi$ - a layer subjected to dehydration, $\text{cm}$.

Once we know the pattern of moisture distribution and the density of the ground skeleton over the entire freezing out layer, the shrinkage value can be calculated as follows:

$$ h_s = K_s \left( I - \frac{\mu^i}{\mu^{sk}} \right), $$

where $\mu^i$ and $\mu^{sk}$ - initial and finite values of the skeleton volumetric weight, before and after freezing.

Thus, on the strength of the above, the value of ground heave can be calculated using this equation:

$$ h_h = 0.09 (W_w - W_{uf}) \xi + 1.09 K_{an} \cdot K_w \cdot \phi_t \cdot \text{grad} \cdot \tilde{t} - K_s \cdot \beta \cdot \Delta W \cdot \xi $$

It has been established experimentally and confirmed by
field (in-situ) observations that as dispersion of grounds grows, so does the percentage of positive strain due to segregation ice accretion (in accordance with the increase of density of the migration moisture flow in loamy sands - loams - clay series), whereas strains produced by massive heave-out become less common. Massive heave-out in loamy sands may account for 70 to 80%, while its percentage in clays does not exceed 12 to 20%. As the dispersion of rocks grows, the value of negative deformation (shrinkage) increases. Shrinkage may partially, and, sometimes, completely compensate for the positive strain. The study of the processes of heat- and mass-exchange, of segregation ice accretion and heaving was undertaken using frozen samples of kaolinite clay \( (W = 0.50; \rho d = 1.25 \text{ g/cm}^3) \), polynminerall clay \( (W = 0.53; \rho d = 1.21 \text{ g/cm}^3) \) and montmorillonite clay \( (W = 0.78; \rho d = 0.72 \text{ g/cm}^3) \). The process of freeze-out was simulated under the same boundary temperature conditions as referred to in the afore-described experiments, moisture of the rocks being equal to full saturation. The findings of the studies have shown that maximum value of the migratory moisture flow density is registered in kaolinite clay, and is equal to \( 36.10^{-6} \text{ g/cm}^2 \cdot \text{s} \), the minimum value is recorded in montmorillonite clay \( (J_w = 22.10^{-6} \text{ g/cm}^2 \cdot \text{s}) \). The density of moisture migratory flow in polynminerall clay measured \( 28.10^{-6} \text{ g/cm}^2 \cdot \text{s} \). The curve of migratory moisture flow density change dies down gently. Kaolinite and hydro-mica clays display moisture re-distribution caused essentially by ambient migratory flow (i.e. at the expense of inflow from the outside); in montmorillonite clay, the main role is played by the internal migration flow (at the expense of re-distribution of moisture contained in the ground). The share of migration ice accretion in the heaving of grounds of different mineral composition is practically the same and is equal to 34, 36 and 30%, respectively. However, the heaving value in these grounds is different. So sharply different values of ground heaving despite the
comparable values of migratory moisture flow density are mainly due to manifestations of the shrinkage process. Thus, owing to shrinking deformation, nearly 16% of the total value of positive deformations are compensated in a freezing-out kaolinite clay (polymineral clay - 27%). However, in montmorillonite clay, shrinking deformations play the greatest role in smoothing ground heaving: here, shrinkage accounts for over 30% of shrinking deformations. As the ambient conditions change, so does the correlation between the positive and negative deformations.

For example, when the temperature gradient increases, the migratory moisture flow density grows; however, the ice accretion value on the whole may drop as a result of fast advance of the freeze-out front. As the rate of freeze-out increases, most of the water is crystallized in situ, which leads to greater deformations of massive heave-out and to smaller shrinkage. The correlation between the values of positive and negative deformations is also influenced by moisture, density, the water table and other factors.

Strain of frozen ground subjected to thawing can be presented in a general form \( S_{oc} \) as follows:

\[
S_{oc} = S_i + S_{om} + S_{cm} + S_s - S_{sw} - S_J,
\]

where we have the following ground strains: \( S_i \) - volumetric phase changes as ice turns to water; \( S_{om} \) - strain due structural transformation (closing of macropores) during thawing ground consolidation affected by own weight alone; \( S_{cm} \) - strain due to structural transformation during thawing ground consolidation affected by the overburden load; \( S_s \) - strain due to shrinkage; \( S_{sw} \) - strain due to swelling; \( S_J \) - strain due to segregation ice accretion in the frozen zone.

It has been proved experimentally that the value of each component of the total ground strain during thawing depends on the temperature regime and the thawing conditions. It is the thawing temperature regime that determines the structural transformations in the thawing gro-
und and in the ground where the thawing process is over. As the temperature goes up, the ground aggregates become loose, overall porosity increases and other transformations in the structure of the pore space take place; this determines, for example, considerable deformations of thawed grounds during compressional compaction.

Just like in freezing out, in the course of thawing of frozen rocks, the formation of three zones can be observed: thawed, thawing and frozen zones. In these zones, deformations of opposite directions take place, like heat-induced settling and shrinkage (negative deformation), heaving and swelling (positive deformation). Laboratory trials with one-sided thawing of frozen samples (4x4x12 cm³) of dispersion rocks with a massive cryogenic structure under boundary conditions: + 2° in the upper butt-end of the sample, and minus 4° in the lower butt-end.

The trials were held in conditions of free-flowing water (an open system) of + 2° reaching the top surface of the samples. The outside migratory flow under the conditions of an open system is used to produce segregation ice accretion in the frozen zone and the swelling of the thawed ground. Under these conditions, the shrinking deformations of the thawing zone are negligible. In the course of kaolinite clay samples thawing, heat-induced settling was observed which was due to pore ice melting. The settling was equal to ~2%, the value of swelling deformation being ~4%. Of great interest are the processes taking place in the frozen zone of the thawing grounds. Under the influence of the temperature gradient, the water migrates from the thawing zone to the frozen zone and, while freezing, forms new interlayers of segregation ice. Analysis of the regularities of mass-exchange processes development has shown that migratory ice accretion increases in the loamy sand - loam - clay series, and values of migratory moisture flows (Jw) are close to the values of flows observed in the course of freezing out. Thus, during the trial with kaolinite clay (W = 0.51 and ρd = 1.25 g/cm³)
a migratory flow of \(40.1 \times 10^{-6} \text{ g/cm}^2 \text{ s}\) was registered; in loam \((\kappa = 0.36\) and \(\rho_d = 1.70 \text{ g/cm}^3\)) the flow was four times as small. Here, the share of deformations conditioned by segregation ice accretion in the thawing clay made up 73\% of the total value of positive deformations, in loam - 41.6\%, and in loamy sand - 33.3\%. While studying the deformation of clay rocks, the effect of mineral composition on these processes was revealed. Subjected to thawing (under the same temperature conditions) were the samples of kaolinite clay \((\kappa = 0.51\) and \(\rho_d = 1.25 \text{ g/cm}^3\)), polymineral clay \((\kappa = 0.52\) and \(\rho_d = 1.28 \text{ g/cm}^3\)) and montmorillonite clay \((\kappa = 0.68\) and \(\rho_d = 0.81 \text{ g/cm}^3\)). Analysis of the changing density of migratory moisture flows over time has shown that as the content of montmorillonite group minerals increases, the value of migratory moisture flow goes down. Thus, in montmorillonite clay the migratory flow is by an order of magnitude smaller that in kaolinite and polymineral clays. This has led to a smaller segregation ice accretion in these clays. Maximum value of deformations conditioned by segregation ice accretion was observed in kaolinite clay, a much smaller value - in polymineral clay. In montmorillonite clay, under the conditions of experiments, no visible interlayers were seen to form. By the thermal settling value, the examined clays may be arranged in the following series: kaolinite polymineral montmorillonite. Because the samples thawed under the conditions of a free-flowing water, moisture increased, and so did the swelling deformation. In the experiments, the resultant value of deformations having opposite directions was positive, i.e. instead of the anticipated (in 8 hours) sinking of the top surface of the samples, the surface rose. The close values of resultant positive deformations in the samples of kaolinite and montmorillonite clays are determined by the differences in the swelling deformations. Swelling deformations of kaolinite clay made up 27\% of the total value of positive deformations, in polymineral clay - 75\%, in montmoril-
Iolite clay - 96%.
A strong effect on the development of deformations during
the thawing of frozen rocks is exerted by their initial
compaction, as it determines the progress of heat-mass
exchange, physico-chemical and physico-mechanical pro-
cesses. As the density of thawing samples of kaolinite clay
grew (from 1.25 to 1.36 and 1.41 g/cm\(^3\)) the migratory flow
from the thawed to the frozen zone was noted to diminish
by more than an order of magnitude. The heaving deforma-
tion in a less compacted sample was the highest.
A change in the thawing conditions (temperature and ab-
sence of free-flowing water) has a significant effect on
the values of developing deformations. The strongest ef-
fect on the deforming thawing rocks is exerted by the
rate of advance of the phase delineation boundary. It has
been established that when the thawing rate exceeded 1.5
\(\text{cm/h}\), no ice interlayers were formed in our experiments.
In this case, deformation of the samples is determined
as a sum total of the swelling and settling deformations.
Deceleration of the thawing rate leads to intensive de-
velopment of all kinds of deformations and, especially,
heaving preconditioned by segregation ice accretion.
A comparison of the results of thawing out of identical
samples \((W = 0.51 \text{ and } \rho = 1.25 \text{ g/cm}^3)\) in the presence
or absence of a free-flowing water makes it possible to
draw the following conclusions. In the samples subjected
to one-sided thawing, in both cases a certain definite
amount of water participates in segregation ice accretion;
this water migrates to the frozen zone, forming ice inter-
layers. Then, these interlayers thaw out as the thawing
front approaches, whereupon the water thus formed again
migrates to the area of lower minus temperatures. However,
under the conditions of a closed system segregation ice
accretion occurs due to internal re-distribution of water.
Dehydration and shrinkage of the thawed zone were obser-
vied, but there was no swelling.
Under the conditions of a closed system, the shrinking
deformation has compensated over 20% of the total value of positive deformations.

Of particular interest are the experimental observations over the deformation of frozen dispersion rocks, interacting with cooled solutions of water-soluble salts of varying concentrations under different external pressure. All experiments were performed in conditions that ruled out a possibility of lateral deformation of the samples. Therefore, a change in the height of the samples fully corresponded to the change in volume.

As laboratory trials indicated, deformation of the samples being in contact with cooled saline solutions and under a constant external load (P = 0.2 MPa) is different. If the concentration of NaCl solution is low, an increase in the volume of the samples to a certain constant value is observed, i.e., deformations are stabilized. As the concentration of the sodium salt solution increases more than 3 times the original value, the positive deformations give way to negative ones, i.e., a diminution of the sample value occurs. Deformation such as this indicates that moisture accumulation is replaced by moisture being pressed off. Experimentally, this is confirmed by moisture re-distribution throughout the height of the samples. When the ambient water solution of high concentration interacts with a "fresh" frozen rock, the rock is subjected to intensive salinization and it is transformed from a frozen to a freeze-out state, the processes of compaction and settling being intensified. Analysis of the changing relative heaving deformations in salinity-affected frozen rocks has indicated an extreme nature of the correlations between their maximum values and the temperature/concentration of the ambient saline solution. Such form of the sample deformation curves is, above all, due to the nature of the process of unfrozen moisture migration from the ambient solutions to the frozen samples. Changes in the intensity of moisture migration depending on the temperature and concentration of the ambient solu-
tion were similarly extreme in nature. Deformation of frozen grounds that come into contact with solutions and brines of NaCl depends to a great extent on the external load applied. For example, as external pressure increases from 0 to 0.2 MPa, the value of maximum deformation diminishes 3 times; as the pressure goes up to 1 MPa, positive deformations are not observed.