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Experimental Studies of Soil Frost Heaving Pressure Development in Confined Space

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Abstract. This article describes the results of experimental studies of the frost heaving pressure development at the soil freezing in confined space. Studies devoted to the investigation of heaving soil influence on the structures acquire special significance at present due to the intensive development of the North and North-East regions of Russia. The conducted researches made it possible to reveal the features of the development of frost heaving pressure of clay and sandy soils under one-sided and uniform freezing in confined space, depending on the degree of their water saturation, temperature regime and possible deformations. It was revealed that in sandy soils the formation of the frost heaving pressure is caused by the freezing of free (gravitational) water and can be determined by the Bridgman-Tammann formula. In clay soils, the development of frost heaving pressure is associated with the freezing of loosely-bound (film) water and can be determined by the method proposed by the authors both in the absence and in the presence of heaving volumetric deformation.

1. Introduction

At present, the North and North-East regions of Russia are being intensively developed. The construction of new production complexes for industrial and civil purposes in the areas of development of rich deposits of minerals has expanded.

One of the problems that are of great scientific, technical and applied importance is research of the interaction between the foundations and structures and freezing heaving soils in order to develop effective methods and measures to control the processes of heaving. That is why studying heaving soil force effects on the structures become more and more important.

A considerable amount of information has been accumulated on the problem of frost heaving and important experimental and theoretical studies have been performed to date, which can be found in [1-7]. The issues of investigating the mechanism and dynamics of frost heaving pressure development on the basis of modern concepts of cryogenic processes occurring in soils freezing in confined space are significantly less studied.

The aim and objective of this study is to establish the patterns of soil frost heaving pressure development, and on their basis to find methods for calculating this pressure in relation to erected structures.

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2. Materials and Methods

To study the regularities in the development of the soil frost heaving pressure in confined space in laboratory conditions, more than 50 experiments were performed with sand with medium-sized particles and pulverescent clay. The granulometric composition and physical properties of the investigated soils in accordance with [8] are given in tables 1 and 2.

Table 1. Granulometric composition of the soils under study.

Soil	Size fraction content (mm)						
	>0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.01	0.01-0.005	<0.005
Sand with medium particle size	36.0	59.4	3.9	0.1	0.6	-	-
Pulverescent clay	0.6	2.4	4.2	5.8	41.8	15.0	30.2

Table 2. Physical characteristics of the soils under study.

Soil	Humidity at the liquid limit W_L (%)	Humidity at the plastic limit W_P (%)	Plasticity index I_P (%)	Soil particle number density ρ_s (g/cm^3)	Soil density	
					minimum ρ_{min} (g/cm^3)	maximum ρ_{max} (g/cm^3)
Sand with medium particle size	-	-	-	2.68	1.60	1.73
Pulverescent clay	38	17	21	2.70	-	-

The studies described in this paper were carried out using an experimental setup consisting of chambers for placing the samples, pressure and temperature sensors, indicating gages, heat insulation, heating elements, a recording equipment complex and necessary automation equipment for operating the heating elements in specified modes. The investigations were carried out on the soil samples of a cylindrical shape 0.2 m in diameter and of 0.3 m height. The chambers for placing the samples were made in a form of a metal cup with a welded bottom. Removable metal covers, reinforced with stiffeners, were attached to the flange of the upper link of the pipe (figure 1).

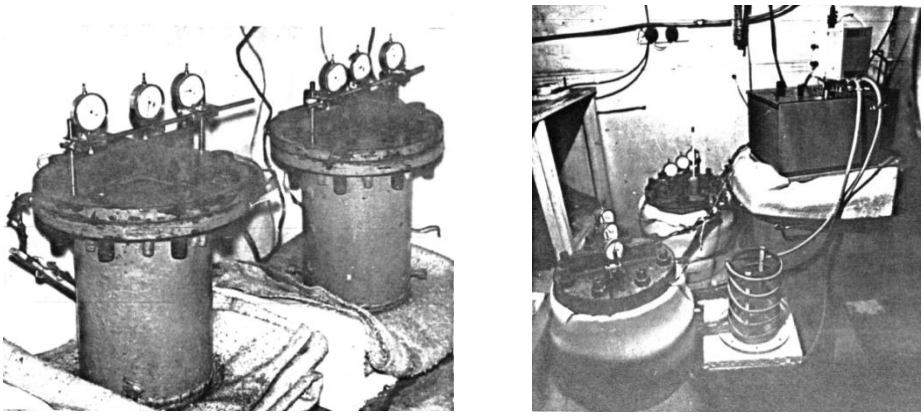


Figure 1. General view of the chamber for placing the samples.

The soil-containing chamber was able to withstand pressures up to 16 MPa, and the relative deformations of its walls and bottom did not exceed the value $1{,}3 \times 10^{-3}$.

The investigations of the heaving pressure were carried out under conditions of one-sided and uniform freezing of the soil.

The air temperature in the refrigerating chamber varied from + 0ºC to -35ºC.

In the case of one-sided freezing of the soil, the experiments were carried out both under conditions of a "confined system" – without a water inflow into the freezing sample from the outside, and under conditions of an "open system" - with a water inflow from below into the soil sample. Together with the study of the heaving pressure, a number of experiments were carried out to determine free heaving deformations. After the experiment, the study and photographing of the soil's cryotextures were carried out.

3. Results

The use of the developed method of complex laboratory studies made it possible to establish the patterns of heaving pressure development in sandy and clay soils that freeze in confined space under various temperature and humidity regimes.

The results of the tests with clay soils are presented below, the characteristics of the soils are given in table 3.

Table 3. Physical characteristics of soils in the tests M1…M5.

Test	Soil	Soil density ρ_s (g/cm^3)	Soil humidity W (%)	Porosity index e	Liquidity index I_L	Degree of saturation S_r
M1	Soft-firm fat clay	1.91	37.5	1.01	0.98	1.0
M2	Firm-stiff fat clay	2.1	24.6	0.61	0.36	1.0
M3	Stiff fat clay	2.1	20.3	0.54	0.16	1.0
M4	Stiff fat clay	2.15	19.3	0.5	0.11	1.0
M5	Sand with medium particle size	2.06	20.2	0.58	-	0.98

As can be seen from figure 2, the initial soil humidity has a strong influence on the nature of the inflow of water into the sample. Thus, in the test M2, during the freezing of firm-stiff fat clay, a rapid inflow of water into the sample was observed during the initial stage of freezing; an inverse phenomenon was observed in the test M1 in the initial period of soft-firm fat clay freezing, namely, wringing of water out of the sample. It can be assumed that the reason for the outflow of moisture from the freezing sample in the M1 test was a higher intensity of the "internal" heaving of the soil.

As can be seen from the graphs, with incomplete freezing of the soil under conditions of a stationary temperature field with temperature gradients close to optimal, no noticeable increase in the soil heaving pressure was observed. The maximum pressure in the tests M1 and M2 did not exceed 1.0 MPa. However, a short decrease in the temperature at the bottom of the samples to -2ºC after 10 days of the experiment caused a sharp increase in the heaving pressure up to 4.0 MPa. As the bottom of the samples was thawing, the pressure dropped to 1.0 MPa and subsequently did not exceed 1.0 MPa during the entire freezing period lasting more than 30 days.

After 30 days of slow freezing of the soil under a steady temperature regime, the soil was completely frozen to -32ºC. The heaving pressure in the M1 test reached 8.1 MPa, and in the M2 test it was 15.7 MPa. Then the soil temperature was raised to -1...-2ºC, and the pressure was reduced to zero by removing the upper covers of the working cups. After removing the covers, the freezing cycle was performed again (down to -32ºC). Then samples of the frozen soil were extracted from the cups, and their cryogenic textures were analyzed.

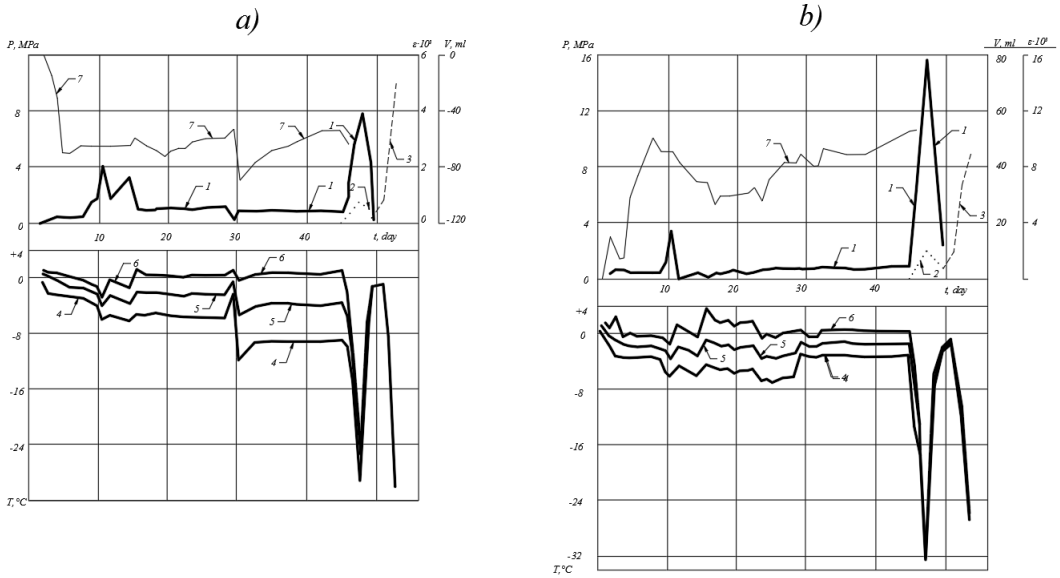


Figure 2. Graphs of the heaving pressure and deformation during one-sided freezing of clay in confined space.
a – test M1; b – test M2
1 – heaving pressure; 2 – heaving relative deformation; 3 – heaving relative deformation after relieving; 4, 5, 6 – temperature of the top, middle and bottom of the soil sample respectively (ºC); 7 - dynamics of water migration, ml.

In the photo (figure 3), a cellular (netlike) cryogenic texture formed in the frozen zone of the samples with their partial freezing under the conditions of an open system is clearly visible. When the soft-firm fat soil was freezing (test M1), the ice layers occurred more closely than in the M2 test with the firm-stiff fat clay soil, and their thickness reached 3 mm, but the one in the test M2 did not exceed 1 mm. In the lower part of the soil samples, zones with a massive cryogenic texture formed, which is also clearly visible in the photo (figure 3).

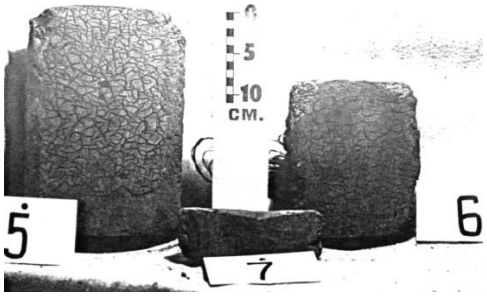


Figure 3. Cryogenic texture in the frozen soil in the tests M1 (5) and M2 (6,7).

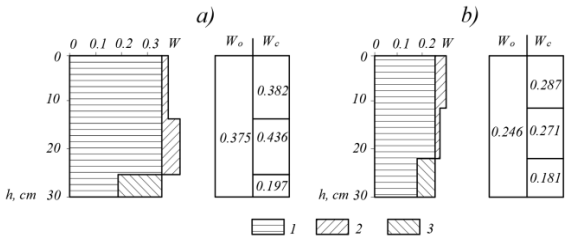


Figure 4. Diagrams of soil humidity change before and after freezing under conditions of an open system in the tests M1 (a) and M2 (b) 1 - initial humidity; 2 - humidity increase; 3 - humidity decrease; W_0 - humidity before freezing; W_c - humidity after freezing.

Figure 4 shows the change in humidity of these soil samples before and after their freezing in the open system. In the upper and middle parts of the samples, the soil humidity after freezing increased in comparison with the initial level by 2...7%; and in the lower part, the soil was dehydrated to the

humidity close to critical. The humidity of the dehydrated lower parts of both samples after freezing turned out to be practically identical.

In the tests M3 and M4 (figure 5), the frost heaving pressure development of semi-solid pulverescent clay was studied, depending on the cyclic alteration of a negative temperature.

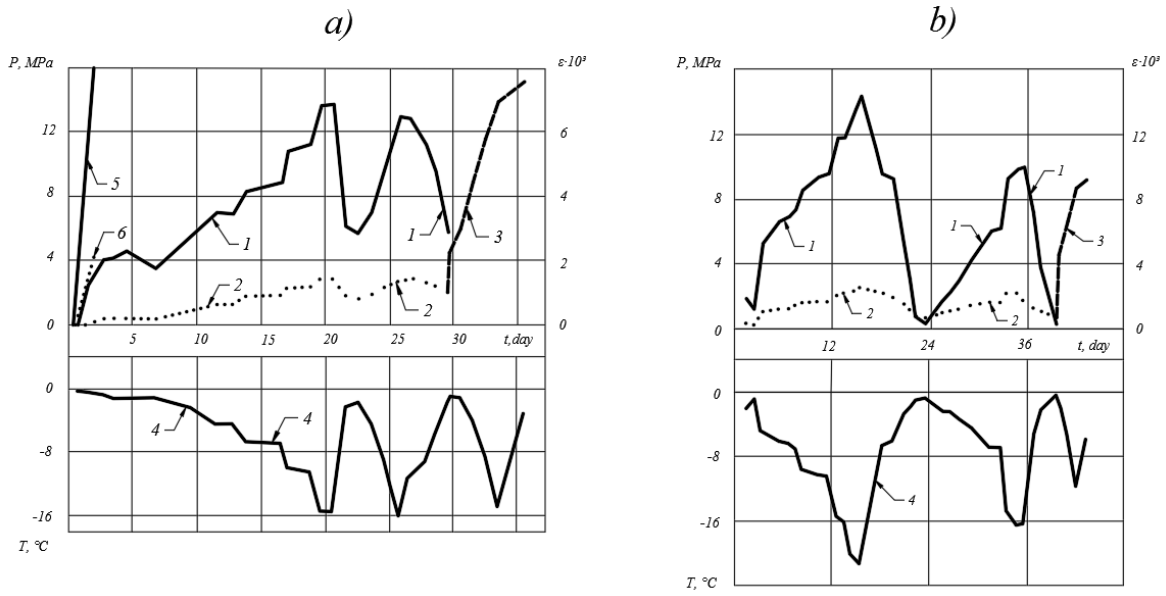


Figure 5. Graphs of heaving pressure and deformation, depending on the cyclic drop in a negative temperature.
a - uniform freezing (tests M3, M5); b – one-sided freezing (test M4) 1 – heaving pressure; 2 – heaving relative deformation; 3 – heaving relative deformation after relieving; 4 - average soil temperature (ºC); 5 - heaving pressure in the test M5; 6 – heaving relative deformation in the test M5.

The study revealed a distinct dependence of the heaving pressure during freezing of the soil on the temperature. The temperature regime of soil freezing in the tests varied stepwise. The shape of the heaving pressure graph is almost the same as the shape of the soil temperature change graph. Thus, the stepwise decrease in the soil temperature from -1.2ºC to -15.2ºC resulted in the increase in the pressure from 4 MPa to 13.8 MPa, and the increase in the soil temperature from -15.2 to -1.6ºC caused the reduction in the heaving pressure from 13.8 to 5.6 MPa.

In the uniform freezing tests of water-saturated sand with medium particle size in confined space, the decrease in the negative soil temperature to -2ºC caused the increase in pressure over 16 MPa (figure 5, graph 5).

4. Discussion

The use of the developed method of complex laboratory studies made it possible to establish the patterns of frost heaving pressure development in sandy and clay soils that freeze in confined space under various temperature and humidity regimes.

The processes that occur when water freezes in soils were investigated in [9, 14], and the processes of water freezing under pressure, depending on the type of crystallization, were reported in [15, 16]. In water-saturated sandy soils, the liquid phase is represented mainly by free (gravitational) water, and the pressure that develops when freezing in confined space is due to the freezing of free (gravitational) water. To estimate the heaving pressure of water-saturated sandy soils during uniform freezing in

confined space, one can use the Bridgman-Tammann formula (1) [17]. The pressure is more than 10 MPa per one degree of the temperature decrease.

$$p^{\infty}_{i,w} = 1 + 127 \cdot T - 1.519T^2 \quad (1)$$

where $p^{\infty}_{i,w}$ – pressure (10^{-1} MPa); T – ice melting temperature (ºC).

In water-saturated clay soils, the liquid phase is represented mainly by bound water, and the pressure that develops when the soil freezes in confined space is due to the freezing of loosely-bound (film) water. The presence of film water in clay soils, which exerts a dominant influence on the development of the frost heaving process, causes the dynamics of the heaving pressure development, which is different from sandy soil. Analysis of experimental data, taking into account modern concepts of cryogenic processes and phase transformations of water, has shown that it is necessary to distinguish the pressure that arises from the crystallization of free water and the pressure arising during the cooling of frozen soil due to the crystallization of loosely bound (film, unfrozen) water.

During the interaction between soil and water, the pressure of ice crystals growing in the pores will be taken both by its mineral part and by firmly bound water, the properties of which are similar to those of a solid body. As the pressure develops, in the frost penetration zone, mineral particles, together with firmly-bound water, form a rigid lattice framework, which receives the pressure and makes it possible for the film water to freely penetrate through the lattice holes to the ice crystals growing in the pores. At that the solid phase (ice) takes the pressure arising from growing ice crystals, and there is no such a pressure in the liquid phase (loosely-bound, film water) [18].

The proposed mechanism and the mechanical model of the soil make it possible to estimate soil heaving pressure in confined space from the standpoint of equilibrium thermodynamics [19] using the following formula:

$$p_i = 1035.76\ln(T) - 6.707T + 0.0031T^2 - 1.66 \cdot 10^{-11}T^3 - 4210 \quad (2)$$

where p_i - heaving pressure (MPa), which develops in the freezing soil at the temperature T (ºK) due to the freezing of film unfrozen water.

The value of p_i, determined by formula (2), is in good agreement with the results of the experiments obtained by the researchers T.Takashi, F.Radd, and D.Ortle [20, 21] (figure 6).

In conditions of complete freezing of soil in confined space, the allowance of volumetric heaving deformation, taking into account the temperature compression of the frozen soil, causes a change in the interphase equilibrium state in the latter and, as a consequence, a decrease in the content of unfrozen water due to its transition into ice. This leads to a decrease in the heaving pressure p_i, determined by formula (2).

In this case, the decrease in p_i is taken into account by the introduction of a reduction factor k_u [22]

$$k_u = 1 - \frac{\rho_w(\varepsilon_v + 3\alpha_m T)}{0.09\rho_d w_{mmw}} \quad (3)$$

where ρ_d and ρ_w – densities of ground skeleton and water respectively (kg/m^3);
ε_v – relative deformation causing the bound water to freeze;
α_m – a temperature coefficient of frozen ground linear contraction (ºC)$^{-1}$;
w_{mmw} – maximum molecular moisture-holding capacity.

The expression for the heaving pressure p_{iu}, taking into account the assumption of possible deformations, takes the form [23]:

$$p_{iu} = k_u p_i \quad (4)$$

The calculation according to formula (4) showed good agreement with the experimental data that we obtained with complete freezing of clay soils in confined space.

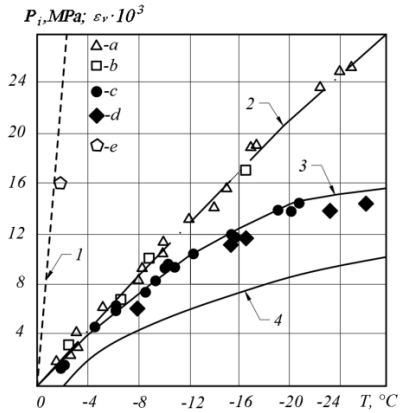


Figure 6. The experimental and calculated data, obtained for one-side ground freezing in confined space.
1 - temperature dependence of $p^{\infty}_{i,w}$ by Bridgmen-Tammann formula (1) for sandy soil;
2 - temperature dependence of freezing soil heaving pressure according to formula (2) (MPa);
3 - dependence of frozen soil heaving pressure on decreasing the negative temperature according to formula (4) (MPa);
4 - calculated dependence for allowed relative volume deformation, $\varepsilon_v \times 10^3$;
a - experimental data, obtained by T.Takashi for water-saturated clayish grounds [20];
b - data by F.J. Radd and D.H. Ortle [21];
c - data for the test M2; *d* - data for the test M4; *e* - data for the test M5.

At partial freezing of clay soil in confined space, i.e. in the conditions of the existence of frozen and thawed zones, the heaving pressure will be determined by the resistance of the thawed soil when it is compressed by the heaving soil. In conditions of impossibility of heaving deformation, the freezing soil, due to its high rigidity, compacts the thawed soil of the buffer zone by the so-called "internal" heaving amount, which leads to a reduction in the heaving pressure to 0.04...1 MPa.

5. Conclusions

Summarizing the results of the studies carried out and the results obtained calculating the pressure of frost heaving during the freezing of soil in confined space, the following main conclusions can be made:

1. In the course of laboratory studies, the features of the development of the heaving pressure were established depending on the one-sided and uniform freezing of clay and sandy soils, the degree of their water saturation and deformation in confined space, and also on the temperature regime both during the freezing of thawed and cooling of frozen soil in confined space.
2. Heaving pressure development during freezing of water-saturated sandy and clay soils has a fundamental difference. In sandy soils, the formation of heaving pressure is caused by the freezing of free (gravitational) water, and it can be definitely determined by the Bridgman-Tammann formula (1), and in clay soils, it is caused by the freezing of loosely-bound (film) water. The quantitative estimate of this pressure can be made from the standpoint of equilibrium thermodynamics and is described by equation (2).
3. The pressure of frost heaving is directly related to the temperature of the freezing soil and the possibility of deformation of the soil. A quantitative estimate of this pressure, taking into account the allowance of deformations, can be made by formula (4). The calculation using this formula showed good agreement with the experimental data obtained at complete freezing of clay soils in confined space.

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