Heaving Pressure Occurring at Frost Penetration in the Clay Soil in Confined Space

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Abstract. The article describes the results of laboratory studies of the frost heaving pressure development at the clay soil freezing in confined space. Intensive construction of industrial and civil buildings in the North and North-East of Russia determines the relevance of research on this topic. The conducted studies allowed us to reveal the peculiarities of frost heaving pressure development, depending on the temperature conditions and physical properties of the clay soil, as well as possible heave deformations. The paper gives dependence of frost heaving pressure development during one-sided and uniform frost penetration in confined space on the degree of its water saturation, temperature conditions and possible deformations. It was revealed that in sandy soils, the formation of 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 that we propose both in the absence and in the presence of heaving volumetric deformation. The experimental technique that we offer makes it possible to analyze the development of the frost heaving pressure of the clay soil when it freezes in confined space.

1. Introduction

The development of the rich natural resources of the North and North-East of Russia has led to the relevance of the construction of new territorial-industrial complexes for industrial and civil purposes. During construction in these areas, one inevitably encounters frozen or seasonally freezing soils with the features of frost heaving.

The force impact of freezing heaving soil on underground structures and foundation structures when constructing in these harsh climatic conditions is a problem that requires a scientific and technical applied solution.

In the field of experimental and theoretical studies of the problem of frost heaving, considerable material has been accumulated, which is reflected in [1–7]. The mechanism and dynamics of the development of frost heaving pressure in clay soil when it freezes in confined space is much less studied.

The purpose of this study is to establish patterns of the frost heaving pressure development when the clay soil freezes in confined space and to develop methods for taking this pressure into account in engineering calculations.
2. Materials and Methods
We carried out the studies of the mechanisms of frost heaving pressure development of the soil in confined space under laboratory conditions using water-saturated pulverescent clay of various consistencies (table 1).

| Test | Soil                        | Soil density, $\rho_s$ (g/cm$^3$) | Soil humidity, $W$ (%) | Porosity index, $e$ | Liquidity index, $I_L$ | Degree of saturation, $S_r$ |
|------|-----------------------------|-----------------------------------|------------------------|---------------------|------------------------|--------------------------|
| 1    | Firm pulverescent fat clay  | 1.94                              | 29.6                   | 0.80                | 0.6                    | 1.0                      |
| 2    | Firm pulverescent fat clay  | 1.93                              | 30.0                   | 0.82                | 0.62                   | 1.0                      |
| 3    | Firm-stiff pulverescent fat clay | 2.1                              | 24.6                   | 0.61                | 0.36                   | 1.0                      |
| 4    | Stiff pulverescent fat clay | 2.1                               | 20.0                   | 0.54                | 0.14                   | 1.0                      |

The experimental unit consisted of chambers for placing samples, pressure sensors installed in a removable lid on the top of the sample, temperature sensors located along the entire height of the sample, indicating gage recording the allowed displacement, thermal insulation, heating elements, a set of recording equipment, and the necessary automation equipment for operation of heating elements at the specified modes. The studies were conducted on soil samples of cylindrical shape with a diameter of 0.2 m and a height for the large-size sample of 0.8 m (figure 1, a), and for the small-size sample - 0.3 m (figure 1, b). The chamber for the large-size sample consisted of three links: the upper links with a height of 0.25 m and the lower one with a height of 0.3 m, and for a small-size one - with one link with a height of 0.3 m.

(a) (b)

Figure 1. General view of the camera for sample placement:
(a) - large-size unit; (b) - small size unit.

The experimental unit was able to withstand pressures up to 16 MPa and the maximum allowance of relative deformations of the walls and the bottom of the unit did not exceed $1.3 \cdot 10^{-3}$.

Freezing was carried out under conditions of one-sided and uniform frost penetration. The air temperature in the refrigerating chamber varied in the range from $+0^\circ C$ to $-35^\circ C$.

The one-sided freezing of the soil took place both in the conditions of the "closed system" - without the influx of moisture into the freezing sample from the outside, and in the conditions of the "open system" - with the inflow of moisture from the bottom into the soil sample. At the same time, we
measured the heaving pressure and the allowed displacement. We carried out a number of experiments to determine the free deformation of the heave. When the test was completed, we studied the cryo-texture of the soil.

3. Results
In the course of the laboratory studies, we established the regularities of the heaving pressure development in clay soils freezing in confined space under different temperature and humidity conditions.

To determine the effect of consolidation of thawed soil on the development of heaving pressure, let us consider the results of test 1 and 2, obtained by one-sided freezing of soil samples with a diameter of 0.2 m and a height of 0.8 m. The samples in these tests had almost identical water-physical characteristics. The freezing conditions differed only in the fact that in test 1, the soil froze through without the possibility of the moisture outflow from the sample (closed system), and in test 2, the outflow of moisture from the freezing sample was possible (open system). As can be seen from the comparison of the results obtained (figure 2), the heaving pressure in the case of incomplete soil freezing in test 1 did not exceed 0.4 MPa, and in test 2 it did not exceed 0.2 MPa.

The behavior of the heaving pressure changes significantly when the zero isotherm reaches the bottom of the sample and the soil freezes through completely. Under these conditions, the heaving pressure in test 1 increased from 0.4 to 3 MPa, and in test 2 - from 0.15 to 0.39 MPa. With an increase in temperature at the bottom of the sample and the formation of a thawed soil zone, the pressure in test 2 decreased to 0.1 MPa (figure 2, b).

![Figure 2](image)

**Figure 2.** Graphs of heaving pressure and distribution of the soil temperature along the sample depth at one-sided clay freezing in closed and open systems: (a) - test 1; (b) - test 2

1 - heaving pressure; 2 - temperature on the soil surface; 3, 4, 5 - soil temperature at depths of 0.3 m, 0.6 m, and 0.8 m, °C

The dependence of the heaving pressure from the decrease in the temperature of the frozen soil in confined space is clearly seen in tests 3 and 4. In test 3 (figure 3, a), the decrease in the temperature of the soil to −2°C caused the increase in pressure to 2.3 MPa. A further decrease in the temperature of the soil to −32°C was accompanied by the increase in pressure to 15.7 MPa, and then with the increase in the temperature of the soil to −2°C, it decreased to 2.5 MPa. The temperature dependence of pressure is especially distinct when the soil is completely frozen in test 4 (figure 3, b). The temperature regime of soil freezing in this test varied in steps and was maintained at each step for several days to equalize the temperature in the sample and to stabilize the pressure at this step. As can be seen from figure 3, b, the shape of the heaving pressure graph practically coincides with the shape
of the graph of the temperature change of the frozen soil. Thus, a stepwise lowering of the soil temperature from −1.2°C to −15°C in the first cycle entailed a similar pressure increase from 0.5 MPa to 11.7 MPa, and the subsequent increase in the soil temperature from −15 to −1.3°C caused a decrease in the heaving pressure from 11.7 to 1.4 MPa. A decrease in the soil temperature in the second cycle from −1.6°C to −16°C was accompanied by an increase in the pressure from 1.4 to 9.5 MPa.

Figure 3. Graphs of the heaving pressure and deformation depending on the negative temperature drop of the frozen soil: (a) - one-sided freezing (test 3); (b) – uniform freezing (test 4)

1 – the heaving pressure; 2 – the allowed relative heaving deformation; 3 - temperature in the refrigerating chamber, °C; 4, 5, 6 – the temperature of the top, middle and bottom of the soil sample °C; 7 - the average temperature of the soil sample, °C

4. Discussion
Using the developed methodology of complex laboratory tests, we established the regularities of the heaving pressure development in clay soils freezing in confined space under different temperature and humidity conditions.

The processes occurring during the freezing of water in soils are described in [8...13] and the processes of freezing of water under pressure, depending on the type of crystallization - in [14, 15].

We examined the processes occurring during soil freezing in confined space and described them in [18, 19].

To quantify the heaving pressure at frost penetration in confined space without taking into account the deformations, we proposed the formula [18]

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

(1)

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

To take into account the effect of possible deformations when the soil freezes in confined space, we proposed the formula [18, 19]
\[ p_u = k_u p_i, \]  

where \( k_u \) - the reduction factor, taking into account the possibility of deformation, and equal to:

\[
k_u = 1 - \frac{\rho_d (e_v + 3\alpha_m T)}{0.09 \rho_d w_{mmw}},
\]

where \( \rho_d \) and \( \rho_w \) – the densities of the soil skeleton and water respectively, kg/m³;
\( e_v \) – the relative deformation causing the bound water to freeze;
\( \alpha_m \) – the temperature coefficient of frozen soil linear contraction (°C)⁻¹;
\( w_{mmw} \) – the maximum molecular moisture-holding capacity.

5. Conclusions

The results of the studies to determine the heaving pressure at frost penetration in confined space allow us to draw the following conclusions:

1. In the course of laboratory tests, the features of the development of pressure in confined space were determined depending on the temperature both during the freezing of thawed soil and cooling of frozen soil with incomplete and complete freezing, as well as with the possibility of some allowable deformation.
2. The formation of heaving pressure when at frost penetration in water-saturated clay soils in confined space has a fundamental difference in the case of incomplete and complete freezing. The value of the heaving pressure when the soil is completely frozen is an order of magnitude greater than the pressure values when the soil is not completely frozen in confined space.
3. We found the clear dependence of the heaving pressure when the soil freezes in confined space on the temperature of the frozen soil. Lowering the negative temperature of the soil causes an increase in pressure and an increase in the temperature of the frozen soil causes a corresponding decrease in the heaving pressure.
4. A quantitative estimate of the heaving pressure when the negative temperature of the frozen soil varies in confined space can be given by formulas (1)-(3).

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