Taking into account nonlinear character of heaving pressure development at frost penetration into the soil in confined space

V Kim¹, M Kim¹, M Kim²

¹The Department of Building Structures and Foundation Engineering named after Professor Yu. M. Borisov, Voronezh State Technical University, 84, 20-letiya Oktyabrya st., Voronezh 394006, Russia
²Sber-tech, 32, build.1, Kutuzovsky Ave., Moscow 121170, Russia

E-mail: marskim@yandex.ru

Abstract. The article describes the results of a study of the nonlinear nature of the development of frost heaving pressure during freezing of soil in confined space. It was revealed that the development of freezing pressure in firm and firm-stiff clay soils is due to various processes that occur in them when lowering the temperatures. In water-saturated firm clay soils, heaving pressure occurs mainly when free water freezes in a closed pore volume, and in stiff clay soils, it is caused mainly by the pressure that occurs when film water freezes. Equations are proposed for determining heaving pressure in firm and firm-stiff clay soils.

1. Introduction
The development of the frost heaving process in freezing soil is associated both with the freezing of free water contained in its pores and with the freezing of film (loose) water, the presence of which is typical for water-saturated clay soils. As is known, freezing of pore water in the soil is accompanied by a pronounced differentiation of salts between its solid and liquid phases. The specific character of film water freezing also determines the specifics of ice formation in freezing heaving soils. Experimental studies of the structure of frozen soil [1-13] showed that in frozen soil, along with areas with ice-cement bonds, there are areas where ice formation is absent and the connection between mineral particles is carried out through a film of water. With the onset of crystallization of water in soils, ice formation begins in pores larger than 100 microns, where, according to studies, water is in a free state. After freezing of free water, a further decrease in temperature causes partial freezing of loose-bound water and leads to the heaving of the soil due to the accumulation of moisture during its migration. With the bounding of heaving deformations, the possibility of free expansion in growing ice crystals is limited, and therefore pressure arises at their contact with microaggregates of mineral particles. Under the influence of this pressure, the mineral particles of soil microaggregates will come closer to a distance at which the electrostatic repulsive forces of the mineral particles come into equilibrium with external forces.

2. Theoretical basis
With a decrease in temperature within the temperature range of the beginning and end of heaving, the film thickness of loose-bound water due to its freezing will be less than the same film that is...
characteristic of soil in a thawed water-saturated state. Considering that the sizes of mineral particles are several orders of magnitude greater than the thickness of the water film, we can assume that the pressure developed in the freezing zone by growing ice crystals does not cause the transfer of loose-bound water to free water. In this case, the magnitude of the force fields of the film water does not depend on external pressure and is mainly due to the nature of the surface of the solid mineral part of the soil, their capillary-porous structure (characteristic of dispersed soils), the quality and quantity of the pore solution.

Thus, in the process of ice formation, microaggregates of mineral particles of soil together with firmly bound water and ice-cement bonds form a rigid lattice framework in the freezing zone, which fully bears the pressure of ice crystals growing in the pores and allows loose-bound water to flow freely through the lattice holes, thereby providing further formation of ice.

A calculated schematic model of the development of frost heaving pressure can be obtained if the resistance of the structural and ice-cement bonds of the soil is conventionally replaced by springs 5 and 7 in Figure 1. In this case, the skeleton of mineral particles and ice crystals growing in its pores can be represented as freely supported cylinders (3), which bear the pressure of the spring enclosed in them (2), simulating the pressure of ice crystals formed by freezing of film water (4).

The proposed mechanical scheme allows us to evaluate the heaving pressure $P_{iu}$ taking into account the positions of equilibrium thermodynamics [14] when loose-bound water freezes in the soil pores in an open system using the equation:

$$p_{iu} = 1035.761\ln(T) - 6.707T + 0.0031T^2 - 1.66 \cdot 10^{-11} T^3 - 4210.$$  \hspace{1cm} (1)

The calculation results by equation (1) are in good agreement with the experimental data obtained by American researchers F. Rudd and D. Ortle [15] and Japanese researchers T. Takashi et al. [16].

3. Results
Comparing the experimental data [17] on the heaving pressure with those calculated by equation (1), it is impossible not to note a certain discrepancy between them.

It is seen from the data (Figure 2) that in the temperature range from 0°C to -20°C with an increase in the initial soil humidity, the measured values of the gradual (with the step of 1°C) increment of the heaving pressure are several times greater than those calculated by formula (1), and in the temperature range below -3°C, we can see reducing discrepancies with the calculated values. In the temperature range from -3°C to -7°C, the difference between the experimental values of the gradual pressure increment from the calculated values reaches 40%, and when the temperature decreases from -7°C to -16°C, the difference increases to 80% or more.
We can give the following explanation. A multiple increase in frost heaving pressure in the temperature range from 0 to -2°C is due to the fact that the pressure in the soil during this period occurs due to freezing of free water in confined space without the possibility of volume expansion, which is accompanied by the development of very high pressure, which can be determined by the Tammann-Bridgman equation [18, 19].

The decrease of the gradual increment in heaving pressure in the experiments compared with the calculated values at lower temperatures can be explained by the fact that, under conditions of complete freezing of the soil in confined space, even a slight allowance of volumetric heaving deformation of frozen soil can cause a change in the interphase equilibrium state in it and, as a result, a decrease in the content of unfrozen water while transiting into ice. During this period, non-freezing free water is completely absent in the soil, and the freezing pressure develops mainly due to the freezing of film water.

![Figure 2](image.png)

**Figure 2.** The change in the gradual increment of the heaving pressure of pulverescent clay with a decrease in negative temperature 1 - increment of the heaving pressure calculated by formula (1); experimental values of the heaving pressure increment: ▲ - I_L = 0.14; ▲ - I_L = 0.5; ○ - I_L = 0.7; ● - I_L = 0.58; □ - I_L = 0.16; ■ - I_L = 0.11.

4. Discussion

Thus, with complete freezing of the soil in confined space, even with some allowance of heaving deformations, there is a phase equilibrium of moisture, depending on the pressure and temperature of the soil. Taking into account the phase equilibrium between ice and water depending on the pressure and temperature in the freezing zone and using the pressure development model (Figure 1) and equation (1), let us evaluate the heaving pressure when the negative soil temperature in confined space is lowered, taking into account a possible allowance of volumetric heaving deformations.

The temperature of the beginning of free water freezing for clay soils with relative humidity ($W/W_l$)>0.5 can be taken equal to the temperature of the beginning of soil freezing $T_{bf}$[20].

$$T_{bf} = T \left( \frac{W}{W_l} \right) \text{ at } T = -0.045.$$  (2)

We assume that the bulk of the free ground water freezes at the temperature of the beginning of heaving $T_{bf}$[20]. The heaving beginning temperature $T_{bf}$, as a rule, is several tenths of a degree lower than the freezing temperature of the soil $T_{bf}$, due to a certain "advance" in the process of crystallization of free water over the freezing process of bound water.

According to the above model, the heaving pressure $P_{ou}$ arising at the moment of complete freezing of the soil will be equal to
\[ P_{ou} = P_{ow} + P_{iuw}, \quad (3) \]

where \( P_{ow} \) – heaving pressure from the freezing of pore water in the temperature range from \( T_{bf} \) to \( T_{bp} \);
\( P_{iuw} \) – heaving pressure from changes in the content of unfrozen water.

Pressure \( P_{ow} \) can be defined as the pressure that occurs when free water freezes in confined space without the possibility of its volume expansion, according to the Tammann-Bridgman equation [18, 19]

\[ p_{iw}^{\infty} = 1 + 127 \cdot T - 1.519 \cdot T^2, \quad (4) \]

where \( p_{iw}^{\infty} \) – pressure, \( 10^{-1} \) MPa; \( T \) – the melting point of ice, °C.

The allowance of relative volumetric deformation of the heaving \( \varepsilon_{vf} \) will lead to a decrease in the content of the liquid phase of the frozen soil by \( W_{fi} \), which, taking into account the expansion during freezing, will be equal to

\[ W_{fi} = \rho_w \cdot \varepsilon_{vf} \cdot \rho_d, \quad (5) \]

where \( \rho_w \) and \( \rho_d \) – density of water and soil skeleton, kg/m³.

In this case, the change in heaving pressure will be due to the freezing of the film water. The result is a decrease in pressure from the calculated value, which is caused by a decrease in the film water content by \( W_{fi} \) due to its partial freezing. Then, pressure reduction can be taken into account by introducing the \( K_u \) coefficient, which characterizes the decrease in the film water content with the allowance of volumetric deformations \( \varepsilon_{vf} \)

\[ K_u = 1 - \frac{W_{fu}}{W_{fw}}, \quad (6) \]

where \( W_{fw} \) is the total content of film water, conventionally assumed to be equal to the content of unfrozen water in frozen soil at the temperature of heaving beginning \( T_{bp} \).

The total heaving deformation \( \varepsilon_{vf} \) at complete freezing of the soil in confined space will be the sum of the heaving deformation \( \varepsilon_{vp} \) allowed at the pressure \( P_{ou} \) and the relative volumetric temperature compression deformation:

\[ \varepsilon_{vf} = \varepsilon_{vp} + 3 \alpha_m T, \quad (7) \]

where \( \alpha_m \) – temperature coefficient of linear reduction of frozen soil, °C⁻¹.

For practical calculations, the total content of film water \( W_{fu} \) can be taken equal to the maximum molecular moisture capacity \( W_{mmw} \). In this case, taking into account (7) and (5), equation (6) will take the form:

\[ k_u = 1 - \frac{\rho_w (\varepsilon_{vp} + 3 \alpha_m T)}{0.09 \rho_d W_{mmw}}, \quad (8) \]

Then the heaving pressure from a change in the content of unfrozen water \( P_{iuw} \) will be equal

\[ P_{iuw} = K_u \cdot P_{iu}. \quad (9) \]

As can be seen from Figure 3, a good agreement between the experimental results and the calculated data allows us to use equation (9) to estimate the heaving pressure when the heaving soil is completely frozen in confined space.
5. Conclusions

The results of the studies to determine the pressure of frost heaving during freezing of the soil in confined space allow us to draw the following conclusions:

1. During laboratory studies, features of the development of heaving pressure in confined space depending on the freezing of thawed soil in an open or closed system were established.
2. A model of the mechanism for the development of heaving pressure in confined space was proposed.
3. The heaving pressure during the freezing of water-saturated clay soils with a firm consistency is mainly due to the pressure that occurs when free water freezes in limited pore volume. The magnitude of this pressure can be determined by the Bridgman-Tammann equation.
4. The heaving pressure during the freezing of water-saturated clay soils of stiff consistency is caused mainly by the pressure arising from the freezing of film water in limited pore volume. A quantitative assessment of this heaving pressure when changing the negative temperature of frozen soil in limited volume can be given by equation (8).

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