Field Research of the Heaving Pressure Occurring at Frost Penetration in the Soil under the Foundation Bed

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Abstract. This article describes the results of field experimental studies of the heaving pressure development during freezing of the soil under the foundation bed. Due to the intensive development of areas North and North-East of Russia, studies on the impact of heaving soils on foundations and underground structures are currently assuming a special significance. The research that we carried out allowed us to reveal features of the heaving pressure development of clay soils during freezing under the foundation bed depending on conditions of freezing. We found that pressure formation depends largely on the location of the frozen area and the compressibility of the melt zone of the freezing soil. In the article, we propose measures to reduce the impact of heaving pressure on the foundation bed.

1. Introduction

The urgency of building new territorial production complexes for industrial and civil purposes in the regions of the North and North-East of Russia is associated with the development of rich mineral deposits.

One of the problems of great importance for construction in the northern areas is the construction of foundations and underground structures in freezing and heaving soils. In this connection, the development of methods for controlling the heaving processes and effective measures to control it is relevant. In the field of experimental and theoretical studies of the problem of frost heave, considerable material has been accumulated, which is reflected in [1-9]. However, field studies of heaving soil pressure on structures do not lose their scientific, technical and applied significance.

The purpose of this study is to establish patterns of development of frost heaving pressure of the soil under the foundation bed in natural conditions, and on their basis, to develop methods for calculating this pressure for erected structures.

2. Materials and methods

Investigations of frost heaving pressure on the bed of foundation models were carried out under natural conditions at the experimental site of the Zagorsk Scientific Experimental Station [17]. The soils of the site are composed of pulverescent loam with high intensity of heaving. The granulometric composition and their physical properties are shown in Tables 1 and 2.

The field installation for studying the heaving pressure (Figure 1), formed under the bed of the non-buried foundation, consisted of three experimental metal foundation-stamps, anchor supports, and a spring dynamometer.
On two foundations-stamps with dimensions of 0.5x0.5 m and 1x1 m, we studied the heaving pressure using a screen to localize the body of the soil freezing under the foundation. For this purpose, we arranged a vertical screen along the contour of the foundation bed down to the depth of seasonal freezing (1.4 m), separating the soil under the foundation from the rest of the massif.

On the third foundation-stamp of 0.5x0.5 m in size, we conducted a control experiment to determine the normal heaving forces under normal conditions.

### Table 1. Granulometric composition of the studied soils.

| Depth of sampling, m | >0.5 mm | 0.5-0.25 mm | 0.25-0.1 mm | 0.1-0.05 mm | 0.05-0.01 mm | 0.01-0.005 mm | <0.005 mm |
|----------------------|---------|-------------|-------------|-------------|--------------|--------------|-----------|
| 1                    | 2       | 3           | 4           | 5           | 6            | 7            | 8         |
| 0.5                  | -       | -           | 1.0         | 8.0         | 56           | 0.05         | 13.7      |
| 1.0                  | -       | 0.5         | 1.0         | 5.9         | 52.7         | 12.8         | 27.1      |
| 1.5                  | -       | 0.1         | 0.4         | 7.0         | 55.4         | 12.0         | 25.1      |

### Table 2. Physical characteristics of the studied soils.

| Depth of sampling, m | Soil density $\rho$, g/cm$^3$ | Soil particle number density $\rho_p$, g/cm$^3$ | Soil humidity $W$, % | Humidity at the liquid limit $W_L$, % | Humidity at the plastic limit $W_p$, % | Plasticity index $I_p$, % | Degree of saturation $S_r$ |
|----------------------|-------------------------------|---------------------------------------------|---------------------|--------------------------------------|-------------------------------------|------------------------|---------------------|
| 1                    | 2                             | 3                                           | 4                   | 5                                    | 6                                   | 7                      | 0.08                |
| 0.2                  | 1.95                          | 2.71                                        | 26.8                | 34                                   | 20                                  | 14                     | 0.95                |
| 0.5                  | 2.02                          | 2.71                                        | 24                  | 36                                   | 20                                  | 16                     | 0.98                |
| 1.0                  | 2.2                           | 2.71                                        | 25.2                | 35                                   | 18                                  | 17                     | 1.00                |
| 1.5                  | -                             | 2.71                                        | 31.2                | 36                                   | 19                                  | 17                     | -                   |
| 2.0                  | -                             | 2.71                                        | 28.4                | 34                                   | 19                                  | 15                     | -                   |

### 3. Results

The field experiment lasted 4 months from November to March. We measured the heaving pressure onto the bed of non-buried foundation-stamps, the air and soil temperature deep in the massif (Figure 2), the value of the soil heaving, the depth of the frost penetration (Figure 3), and also soil humidity after freezing at different depths (Figure 4). The experiment showed that the depth of soil freezing steadily increases during the whole season of negative air temperatures, and fluctuations in the outside temperature have little effect on the temperature of the deep soil layers and, accordingly, on the depth of the frost penetration (Figure 3). With an increase in the thickness of the frozen soil layer, the heaving (the surface lift) also increases (Figure 3). As is known [10-16], an increase in the thickness of the layer of frozen soil under the bed of the foundation leads to an increase in the normal heaving forces. However, in addition, fluctuations in the temperature of the outside air have a significant influence on the magnitude of the heaving pressure. As can be seen from Figure 2, the graph of the heaving pressure on the base of the non-buried foundation-stamp in the control test without the screen reflects very closely the graph of the outside air temperature. Thus, for example, in the 6th decade of the test, when the soil froze to a depth of more than 0.6 m (Figure 3), during the thaw, the air temperature rose to positive (Figure 2, b). At the same time, the heaving pressure on the control stamp with a size of 0.5 x 0.5 m decreased from 0.6 to 0.29 MPa, and the pressure on the stamp with the screen with a size of 0.5 x 0.5 m decreased from 0.16 MPa to 0.10 MPa (Figure 2, a). The pressure on the big stamp with the screen did not practically reflect the fluctuations in the air temperature.
Figure 1. The scheme of the experimental setup for studying the frost heaving pressure on the foundation bed in the field.

1 – foundation-stamp with a size of 0.5x0.5 m without the screen; 2 – foundation-stamp with a size 1x1 m with the screen; 3 – foundation-stamp with a size 0.5x0.5 m with the screen; 4 – thrust beam; 5 – anchor device; 6 – dynamometer; 7 – the screen along the contour of the stamp; 8 – thermometric well; 9 – surface marks (heave-meters)

In the 9th decade of experience during the thaw, the outside air temperature again increased to positive (Figure 2, b). The pressure on the control stamp decreased from 0.69 MPa to 0.31 MPa, and on the stamp with the screen with a size of 0.5x0.5 m – from 0.22 MPa to 0.14 MPa. The depth of soil freezing at this time was equal to 0.85 m (Figure 3). The decrease in pressure lagged 1-2 days behind the increase in temperature.

The freezing of the soil to a depth of 130 cm was accompanied by a change in the humidity of the soil in comparison with the initial one (Figure 4). At a depth from 0 to 60 cm, an increase in humidity was observed; from 60 to 100 cm – a decrease; and deeper – the humidity remained constant.

4. Discussion
The results of the field experiments show that during the entire period of the soil freezing, the heaving pressure on the bed of the control stamp is about 3 times higher than the pressure on the bed of the same size stamp with the screen along the contour of the bed. The maximum pressure on the bed of the stamp without the screen from the action of normal heaving forces during the winter period was 0.69 MPa. For stamps with the screens along the bed perimeter, the maximum pressure on the bed was significantly lower and amounted to 0.24 MPa.

Let us consider this issue in more detail. If the volume of soil during the crystallization of moisture increases freely and evenly, then internal forces in the soil do not arise. Here there is only a simple expansion of the soil, overcoming the weight of the overlying layer. With the restriction of free expansion and the exclusion of deformations, heaving forces are formed in freezing soil.

Under natural conditions, deformations and heaving forces develop in the zone of freezing between the layers of solid-frozen and thawed soil [18-21]. The arising stresses in this zone are transmitted to the solid-frozen layer on top, and to the lower buffer layer of thawed soil. These stresses arise in freezing soils only when there is resistance to the expansion of the water that passes into the ice, are numerically equal to this resistance and vary from zero (in the absence of resistance) to a certain value determined by the deformation properties of the medium and heat transfer conditions.
Figure 2. The results of the tests with non-buried foundations-stamps.

a) – the change in the heaving pressure on the bed during the winter period;
   1 – stamp 1 with a size of 1x1 m with the screen; 2 – stamp 1 with a size of 0.5x0.5 m with the screen;
   3 – stamp 3 with a size of 0.5x0.5 m without the screen

b) – the change in temperature of the air and freezing soils over the same period
   4 – the air temperature at the soil surface;
   5, 6, 7 – the soil temperature at depths of 0.5, 1.0 and 1.5 m

Figure 3. The heaving deformation and depth of soil freezing over the winter period.

1 – displacement of the soil surface;
2 – depth of frost penetration

Figure 4. The distribution diagram of changes in soil moisture before and after freezing.

1 – initial humidity; 2 – increase in humidity;
3 – decrease in humidity
W – the temperature before freezing;
Wc – the temperature after freezing
At frost penetration in a heaving soil below the foundation bed, the latter turns out to be standing on a kind of a slab of frozen soil, the size of which significantly exceeds the area of the bed itself. Therefore, in this case, the normal heaving forces will be determined not by the development of stresses in the freezing zone, but by the strength of the structural bonds of the frozen ground, i.e. the resistance of the frozen soil layer to the displacement along the foundation bed contour. The freezing of the soil under the bed of the foundation in a volume isolated from the rest of the massif, for example, by a vertical screen installed around the perimeter of the bed, causes a different development of heaving stresses. In this case, during the entire period of freezing, the area of the slab of solid-frozen soil will be limited and equal to the foundation bed area. In this case, the heaving pressure on the foundation bed will be determined by the stresses arising in the zone of freezing on the area corresponding to the area of the foundation bed. Therefore, the heaving pressure on the foundation bed without the screen significantly exceeds the pressure on the foundation bed, along the contour of which the screen is installed.

5. Conclusions
The results of studies to determine the frost heaving pressure during soil freezing under the foundation bed allow us to draw the following conclusions:
1. The pressure of frost heaving depends on the thermal regime of freezing. Increasing the external temperature significantly reduces the pressure value regardless of the depth of frost penetration.
2. The mechanisms of formation of frost heaving pressure on the base of the stamp, which has the screen along the contour to the depth of freezing, and not having such a screen, are fundamentally different.
3. The value of frost heaving pressure on the stamp with the screen is about three times lower than the pressure on the stamp without the screen.
4. Installing a screen to eliminate the effect of the strength of the structural bonds of frozen soil on the development of heaving pressure should be considered as one of the measures to reduce the effects of heaving on foundations.

References
[1] Orlov V O 1962 Cryogenic Heaving of Fine-Dispersed Soils (Moscow: Academy of Science USSR) p 187
[2] Ershov E D 2002 General Geocryology. Manual for High School (Moscow: Moscow University Press) p 682
[3] Orlov V O, Yelgin B B and Zheleznyak I I 1987 Heaving of Soils in the Calculations of the Foundations of Structures (Novosibirsk: Nauka) p 133
[4] Orlov V O, Zheleznyak I I, Filippov V D and Fursov V V 1991 Heaving Soil as the Foundation of Structures (Novosibirsk: Nauka) p 130
[5] Zheleznyak I I 1990 Reliability of Frozen Foundations of Structures (Novosibirsk: Nauka) p 170
[6] Zheleznyak I I, Kholodovsky S E 2015 Nature and model of the propagation of temperature waves in kurums Scientific notes of Zabaykalsk State University Series: Physics, Mathematics, Techniques, Technology 3 (62) pp 44-47
[7] Zheleznyak I I 2015 Block massif of rocks: Research and modeling of cryogenic heat transfer Bulletin of ZabSU 11 (126) pp 23-29
[8] Zheleznyak I I 2015 Devices and methods of protecting structures from dangerous cryogenic processes in soils Proc. of XV Int. Scientific and Practical Conf. “Kulagin readings: Equipment and Technologies of Production Processes” (Zabaykalsk: Zabaykalskiy State University) pp 272-276
[9] Zheleznyak I I, Gurulev A A 2015 Mechanical and microwave devices for determining the physic-mechanical properties of frozen soils and ice Kulagin readings: equipment and technologies of production processes Proc. of XV International Scientific and Practical
Zheleznyak I I 2016 On the study of karst cryogenesis in the study of the evolution of the biosphere in the cryosphere of the Transbaikal speleological province The evolution of the biosphere and technogenesis (Chita)

Zheleznyak I I 2016 Features of soil cryogenesis in the natural conditions of Central and Southern Transbaikalia The evolution of the biosphere and technogenesis (Chita)

Zheleznyak I I 2016 About technology and technologies to ensure the stability of structures on frozen soils in the geocryological conditions of Eastern Siberia Kulagin readings: equipment and technologies of production processes Proc. of XV International Scientific and Practical Conference Zabaykalsk State University pp 250-254

Zheleznyak I I, Maneluk B B 2017 Investigation of the stability to dynamic effects of the kherotic cave Kheatei under the explosive method of developing the Ust-Borzinsky limestone deposit in Eastern Transbaikalia Lithosphere 17 4 pp 137-143

Zheleznyak I I, Chernykh E N and Chechelnitsky V V 2017 Investigation of a combination of seismic and geocryological conditions for Northern Transbaikalia Soil Mechanics and Foundation Engineering 5 pp 21-25

Luk`yanov P Yu, Zheleznyak I I and Gurulev A A 2017 Device for layerwise measuring the physical properties of the ice massif in conditions of natural occurrence Instrumentation and Experimental Technique 6 pp 90-93

Nevzorov A L 2000 Foundations on Seasonally Frozen Soils. Manual (Moscow: ACB Publ) p 152

Kim V H 1988 Heaving Pressure Determination at Freezing of Soil in Confined Space: Tech. Sci. Cand. Diss (Moscow: Gersevanov NIIOSP) p 270

Orlov V and Kim V 1988 Soil Mechanics and Foundation Engineering 25 129–135

Kim V and Kim M 2017 Method of evaluation of ground frost heaving pressure on ice-ground barrier of an underground construction and well strengthening walls Int. Sci. Conf. Energy Management of Municipal Transportation Facilities and Transport EMMFT 2017. Advances in Intelligent Systems and Computing ed V Murgul and Z Popovic (Springer, Cham) 692 998-1008

Kim V, Kim M and Kim M 2018 Thermodynamic evaluation of the pressure occurring at frost penetration in confined space of the soil Proc. of Int. Conf. on Civil, Mechanical and Material Engineering ICCMME 2018, Jeju-do, Korea, 16–18 March 2018 1973 02008-1–5