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Fracture mechanics of pile foundations on permafrost soils by the example of Norilsk

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Abstract. In Norilsk, more than 30% of the housing stock is in the state of severe disrepair. The analysis of possible causes of failures and deformations of pile foundations in the city of Norilsk is presented. The numerical calculation of the warming of permafrost soils is carried out. The thawing of these soils only due to climate warming cannot result in critical deformation of pile foundations.

1. Introduction

The main construction was carried out in the period from 1955 to 1990 on the territory of the municipality of Norilsk. Buildings and structures are built on pile foundations on the principle of maintaining the frozen state of the soil base. The main design solution for the foundations of buildings and structures are combined piles: the lower part of the pile is made of monolithic concrete, the upper part - of precast concrete piles of joined piles.

The process of climate warming is most pronounced in the Northern territories. The trend observed of air temperature is on average 0.6 °C for 10 years. There is also a positive gradient of snow precipitation. This led to the fact that there was an increase in the active layer by 13 cm for the period from 2002 to 2016 in Norilsk [1].

According to the survey, the soil temperature at the depths of 10-15 meters ranges from minus 10 to plus 6. Some soils, especially saline ones, acquire plasticity at temperatures above minus 1.5 °C. The increase in the temperature of the active layer and its power resulted in decreasing in the bearing capacity of the base in terms of the resistance of the frozen ground to shear and the surface area of freezing [2]. In addition to natural factors, man-made and anthropogenic factors have a great influence: the impact of the operation of facilities and structures, violation of the rules of operation of pile foundations (limitation of ventilation of technical undergrounds, the lack of organized runoffs), the destruction of networks.

The safety coefficients in Soviet Russia rarely exceeded 1.56 making many foundations in Russia especially vulnerable to climate change [3]. The rapid change of climatic conditions can thus affect the stability of structures designed on the base of climatic regulations from past decades and relatively low safety coefficients.

In recent years 120 multi-storey residential buildings (about 10% of the city's housing stock) have been demolished. More than 30% of the total number of existing 859 apartment buildings of the municipality of Norilsk, are in critical condition.

2. Methods

2.1. Model

The process of melting or crystallization takes place respectively in thawing/freezing of permafrost soils. In this paper to model these processes the enthalpy - porosity formulation is used [4, 5]. In this method, the melt boundary is not explicitly tracked. Instead, a value called the volume proportion of the liquid fraction is introduced, which indicates the volume fraction of the cells in the liquid state. The liquid fraction is calculated for each iteration, based on the enthalpy balance given by equation (1). In the two-phase zone the liquid fraction has a value from 0 to 1. It is modeled as a "pseudo"-porous medium where the porosity decreases from 1 to 0, which indicates the solidification of the material. When the material is completely solidified in the cell, the porosity becomes equal to zero and therefore the velocity also drops to zero. The two-phase liquid-solid zone is considered as a porous zone with the porosity equal to the volume proportion of the liquid fraction. The corresponding sources of energy and momentum flow (inflow) are added to the energy conservation and momentum conservation.

For solidification/melting problems, the energy equation is written as:

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{\upsilon} H) = \nabla(k \nabla T), \tag{1}$$

where: H − enthalpy; ρ − density; $\vec{\upsilon}$ − the fluid velocity.

The enthalpy is in its turn determined as:

$$H = h + \Delta H, \tag{2}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT, \tag{3}$$

where: ΔH − latent heat of phase transition, which is defined by the equation (5); h_{ref} − standard enthalpy of substance formation; T_{ref} − standard temperature; c_p − specific heat at constant pressure.

Volume fraction of liquid phase β, can be defined as:

$$\beta = 0, \text{ if } T < T_{solidus};$$
$$\beta = 1, \text{ if } T < T_{liquidus}; \tag{4}$$
$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, \text{ if } T_{solidus} < T < T_{liquidus}.$$

The latent heat content in the equation (2) can now be written in terms of the heat of the phase transition, L:

$$\Delta H = \beta \cdot L, \tag{5}$$

The enthalpy-porosity approach simulates a two-phase region (region partially hardened) as a porous medium. The porosity in each cell is set equal to the fraction of the liquid phase in that cell. In the regions fully solidified, the porosity is equal to zero. The pulse outflow due to the decrease in porosity in the two-phase zone has the following form:

$$S = \frac{(1-\beta)^2}{(\beta^3 + \varepsilon)} A_{mush} (\vec{\upsilon}), \tag{6}$$

where: β – volume of the liquid phase; ε – numerical parameter (0.001), to prevent division by zero; A_{mush} – constant of the two-phase region.

2.2. Boundary condition

The annual course of the average monthly temperature of the soil surface can be mathematically described, as well as the annual course of the air temperature, by a harmonic function:

$$t_{0,\tau} = t_0 \left[1 + \frac{A_0}{t_0} \cos\left(\frac{2\pi\tau}{\tau_0} - \varepsilon \right) \right], \tag{7}$$

where: A_0 – the amplitude of the fluctuations in the temperature of the soil surface; t_0 – average annual temperature; τ – time; τ_0 – period of fluctuations; ε – initial phase of fluctuations.

At the lower boundary of the area the value of the heat flow is set, taking into account the temperature gradient:

$$g = \frac{\partial t(l_2, \tau)}{\partial x}. \tag{8}$$

Let us note the main points of the numerical method. The difference analog of the convective-diffusion equations is found by the finite volume method for unstructured grids. In this case, the resulting scheme is automatically conservative. The essence of the method is to divide the computational domain into control volumes and integrate the initial conservation equations for each control volume to obtain finite-difference relations. Diffusion flows and source terms are approximated by finite-volume analogs of central-difference relations with the second order of accuracy. The difference equations obtained as a result of discretizing the initial system of differential equations are solved iteratively using an algebraic multigrid solver.

The geometry of the computational domain is shown in Figure 1. The geometric dimensions of the model are: the depth is 40 meters, the radius is 25 meters. The piles combined were considered: the bottom of the pile is performed in situ concrete of grade B22.5, F300, W8; the upper part – of precast reinforced concrete piles C12-35 in casing steel pipes with a 720 mm diameter and 8 mm wall thickness.
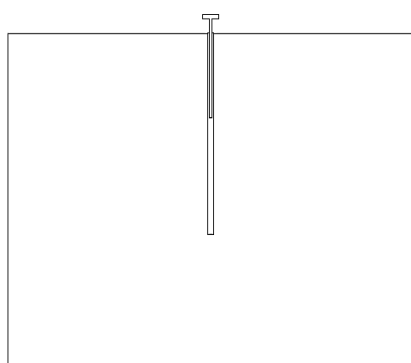

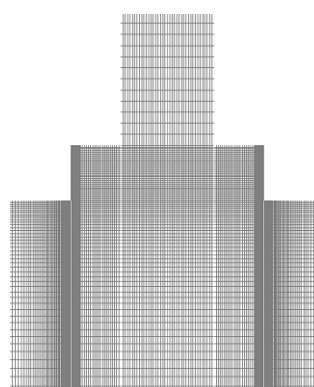**Figure 1.** The geometry of the computational domain.

Figure 2. Fragments of the grid.

Calculation of thermal-hydraulic processes in soil thawing around the pile was carried out on a grid consisting of 250,000 cells with a time step of 20 seconds. Fragments of the grid are shown in Figure 2.

Use was made of the data on the geological section of the soil at the location of the pile in the construction of the model. Thermal and physical properties of rocks were set based on the data presented in Table 1. Ice was taken to be 20%. The temperature of permafrost soils at the initial moment according to the data of geocryological monitoring was set homogeneous in depth and equal to minus 0.2 °C. The calculations were carried out taking into account seasonal fluctuations in the temperature on the surface of the well, taken according to long-term meteorological observations.

Table 1. – Input data (thermodynamic properties) to calculate the halo
of thawing permafrost soils around the piles.

The ice content of rocks	0.20
The temperature of rocks in the frozen state, °C	-0.2
The temperature of the beginning of melting of frozen rocks, °C	0
The thermal conductivity of frozen rocks, λm, W/(m×K),	1.93
Density g/cm^3	1.8
Volume heat capacity of frozen rocks, α, MJ/(m^3×K)	2.31
Brief name of the soil	sandy loam, loam, sand, clay

3. Results and discussion

The calculations have shown that only global warming factors are not able to have a critical impact on the bearing capacity of the pile foundations. Figure 3 shows the influence of the temperature of the super-foundation structure on the thawing of permafrost soils. Foundation failures are not caused by permafrost warming but by climatic effects on foundations material in the active layer and in a crawl space unaccounted for thermal stresses.
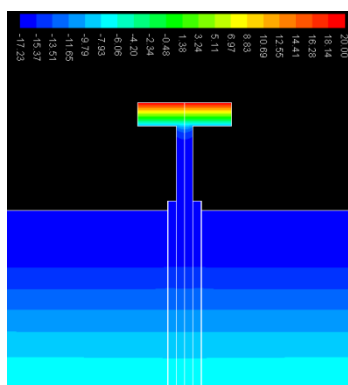

Figure 3. Influence of the temperature of the over-foundation structure on the soil thawing.

Taking into account various anthropogenic factors, using coefficients, the picture of the thawing of permafrost soils is obtained which can correspond to the existing patterns of the destruction of pile foundations. In Figures 4-11 calculations of the liquid phase distribution in the thickness of the base and the soil temperature depending on the month are presented. It can be seen from the figures that the main temperature front propagates along the metal casing.
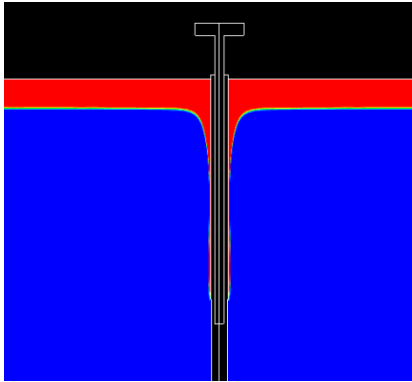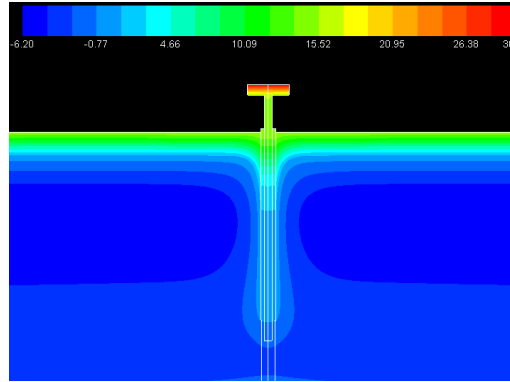
Figure 4. Distribution of the liquid phase. August.
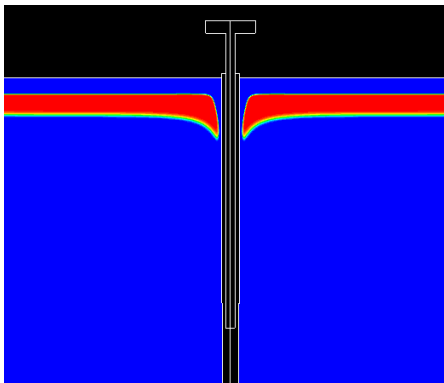

Figure 5. Temperature distribution. August.

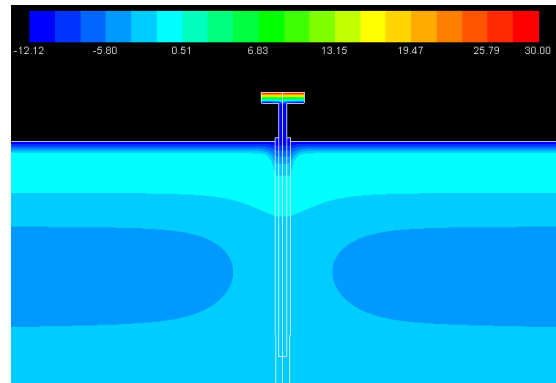
Figure 6. Distribution of the liquid phase. September.

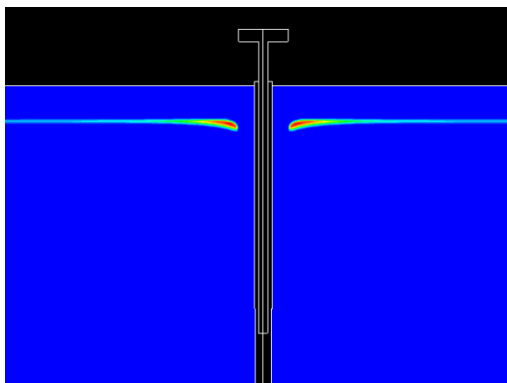**Figure 7.** Temperature distribution. September.

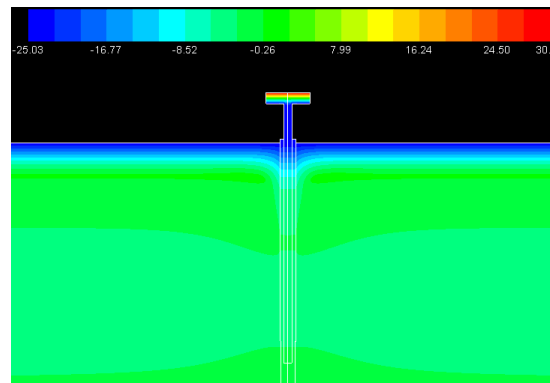**Figure 8.** Distribution of the liquid phase. November.

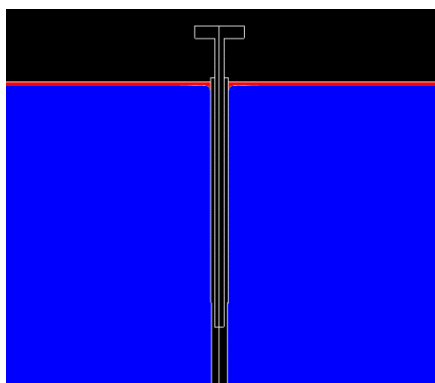**Figure 9.** Temperature distribution. November.

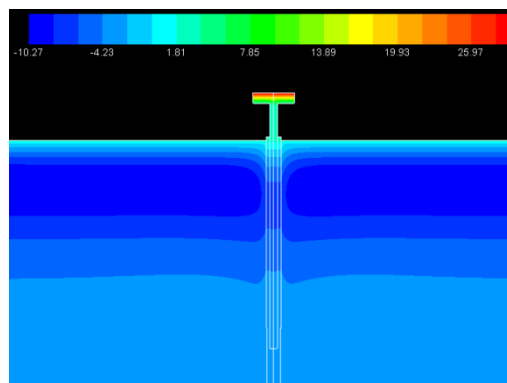**Figure 10.** Distribution of the liquid phase. May.

Figure 11. Temperature distribution. May.

4. Conclusions

The calculations have shown that when taking into account anthropogenic factors the soil of the footings can be thawed to a depth of 15 m. With seasonal freezing of the thawed soils, uneven forces of frost heaving on the surface of soil and piles freezing occurs. This causes deformation of pile foundations, leading to the destruction of load-bearing structures of buildings. Numerous breakdowns and deformations in Norilsk are associated with permafrost changes due to design errors and poor maintenance of buildings, which are more powerful factors than the natural change in permafrost temperature.

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