Evaluation of Temperature and Humidity Effects on High Pile Foundation Platforms in Yakutia

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Abstract. The finite-element analysis of the stress-strain state of the pile foundation structures of the building is performed in the work, taking into account the different humidity of concrete and soils under conditions of unsteady temperature variation of the outside air.

1. Introduction

One of the unsolved problems of reinforced concrete in Yakutia remains the assessment of the temperature-humidity effects in structures located outdoors and in the ground. This applies to the construction of both newly constructed buildings and in operation. The acutest problems are manifested in the design, erection, and operation of foundation structures. It is the foundation structures of buildings that are exposed to climatic low temperatures, the influence of over-frozen ground, often saline water, are in the most difficult operating conditions. A feature of foundation structures in permafrost conditions in the presence of a high ventilated underground (1.2 m) necessary, both for soil conservation in the frozen state and for ensuring the fracture toughness of foundation beams and piles against temperature deformations.

In addition to the height of the ventilated underground, the second factor that ensures the load-carrying capacity of pile foundations is the size of the temperature block of the foundations. In existing standards, there are no requirements for its establishment. The main document regulating the rules for calculating and constructing pile foundations in Yakutia remains RM 2-77 [1], published back in 1977. The album was developed based on the research materials of the Research Institute of Concrete and Reinforced Concrete, on the basis of which "Recommendations on the calculation of reinforced concrete pile foundations erected on permafrost soils, taking into account temperature and humidity effects" were subsequently issued [2].

In 2009, building code SP 52-105-2009 "Concrete Structures for Cold Climate and Permafrost Soil" was published, which combines the main requirements for taking into account the effect of cold climate on the work of reinforced concrete structures in heavy conditions of permafrost soils. A new set of rules introduced a number of new requirements and provisions for the calculation and design. At the same time, in SP 52-105 there are inaccuracies that reduce the possibility of its practical use, in addition, the provisions of this document are based on a piecemeal examination of the work of pile foundations in permafrost soils, taking piles as stakes embedded in the ground.

In modern conditions of development of computer systems, the emergence of new knowledge about materials, there is an urgent need to study the real work of foundations on high grillage. This will allow us to review the existing limitations and design the foundations of buildings and structures more adapted to permafrost soils.

The stress-strain state of foundation structures can most correctly be estimated for models that realize their joint work with the ground grounds. With temperature-humidity influences, the traditional calculation for horizontal impacts (SP 24.13330.2011, SP 25.13330.2012) will not yield acceptable results, since deformations occur in time depending on the air temperature. The latter, in turn, causes a change in the physical and mechanical properties of concrete and soil, both in time and in space. To determine the temperature field of the ground, a nonlinear and non-stationary thermal calculation is required that takes into account changes in physical properties from the phase state of the ground and the latent heat of the phase transition (Stefan's problem).

To simulate the joint work of the pile with soil, medium-sized sand of medium size is considered with the following physical characteristics: thermal conductivity of frozen soil λ_f = 2,285 W/(m°C); thaw ground λ_{th} = 2,053 W/(m°C); Specific heat of frozen soil C_f = 1461,06 J/(kg°C); Specific heat of thawed soil C_{th} = 2089,56 J/(kg°C); density of dry soil $\rho_{d,th,f}$ = 1470 kg/m^3; total moisture content W_{tot}= 0,28; humidity due to unfrozen water W_w= 0,05; the temperature of the phase transition is T_{bf} = –1,2°C.

The model for the Stefan problem is formed without explicitly invoking the front-tracking condition. Such an approach was used in [3, 4, 5, 6]. The phase transition is taken into account by introducing the effective heat capacity $C_{eff}(T)$, which includes the latent heat of phase transition L_0.

The effective heat capacity $C_{eff}(T)$ is described by the equation:

$$C_{eff}(T) = C_{th} - (C_f - C_{th})w(T) - \theta_s \rho_{d,th,f} L_0 \frac{\partial w(T)}{\partial T}; \tag{1}$$

and the coefficient of thermal conductivity:

$$\lambda(T) = \lambda_{th} + (\lambda_f - \lambda_{th})w(T), \tag{2}$$

where C_{th} and C_f are the specific heat of thawed and frozen ground; λ_{th} and λ_f – thermal conductivity of thawed and frozen ground, respectively; θ_s – is the volumetric soil moisture content; $\rho_{d,th,f}$ – is the density of dry ground; $w(T)$ is the dependence of the fraction of frozen water on temperature, which can be approximated by the following empirical relationship:

$$w(T) = \begin{cases} 1 - \dfrac{1}{1 + A(T_{bf} - T)}, & T \le T_{bf} \\ 0, & T > T_{bf} \end{cases} \tag{3}$$

where T_{bf} is the phase transition temperature; A is the smoothing parameter

The calculated region of the thermal problem is considered as for a one-dimensional problem. The lateral faces are located close to the frame, since they do not have a significant effect on thermal calculation. In terms of the dimensions of the calculation area are separated from the center of the piles by 2 m. The depth of the area is 18 m.

At the upper boundary of the soil region, the heat exchange condition with the surrounding medium is specified, which is determined by the average monthly outside air temperature $T_1(t)$ and the heat transfer coefficient $\alpha_в$. The heat transfer coefficient between the soil and air is taken as $\alpha_в$ = 10 W/(m^2°C) (the surface of the earth is not covered with snow and is not covered by vegetation);

On the surface of the reinforced concrete frame, located at a height of 0.5 m and above the ground level, the temperature $T_2(t)$, which is different from the average monthly outside temperature $T_1(t)$, varies according to the equation (4), because according to SP 20.13330.2016, the temperatures in absolute value exceed the average monthly temperatures.

The temperature data are approximated by a cosine wave:

$$T_i(t) = A \cdot \cos 2\pi \frac{t - t_0}{t_{year}} - B \tag{4}$$

where t_0 = 1641600 – seconds from the beginning of the year to the conditional coldest day (January 19 – "Epiphany frosts"); t_{year} = 31536000 – seconds per year; A is the amplitude of the oscillations; B – average annual temperature: for the function $T_1(t)$: A = –30.444; B = –9.283 – according to the approximation of the average monthly temperatures of outdoor air SP 131.13330.2012 for the city of Yakutsk; for $T_2(t)$: A = –41.175; B = –13.675 – according to SP 20.13330.2016 at design temperatures t_c = –54.85 °C and t_w = 27.5 °C.

At the lower boundary, the ground temperature is set according to the thermometric data T_0 = –2,9°C., °C, and zero heat fluxes to the side surfaces. The initial temperature of the design area is assumed to be T_0 = –2,9°C.

The calculation scheme is shown in Figure 1. In this model, a foundation with a temperature of 18 m is presented. For the calculation, 1/4 part of the object, cut along the planes of symmetry, is considered. The calculation is carried out for 10 annual cycles. The results of the heat calculation are shown in Figures 2 and 3.

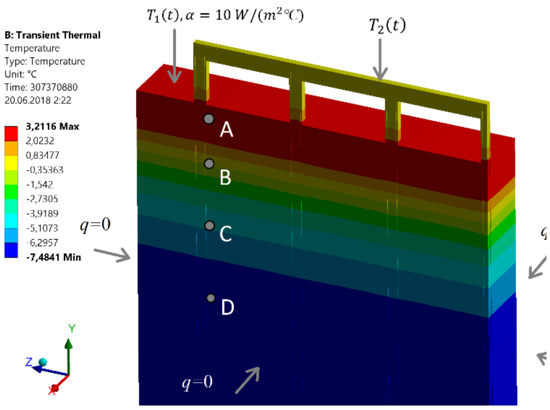

Figure 1. Temperature field on September 1

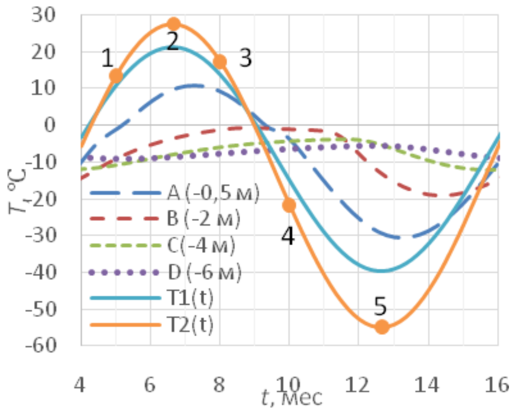

Figure 2. Temperature changes at certain points (Figure 1). The numbers indicate the stages of loading

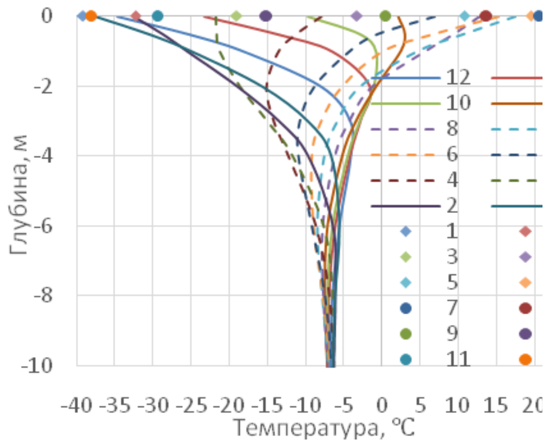

Figure 3. Soil temperatures by months (the figures show the past number of months from January 1, the line – the temperature in the ground, the points – the air temperature)

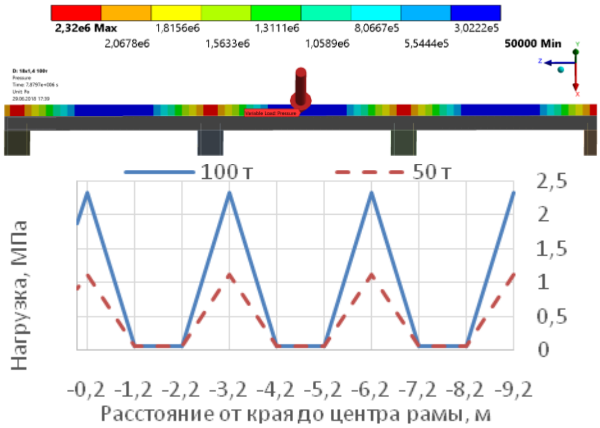

Figure 4. Diagram of the distribution of constant vertical loads at 100 tons and 50 tons per pile

Structural analysis is performed taking into account the plastic deformations of the soil and concrete to the "first" freezing. To the nodes of the lateral surfaces of the model are imposed restrictions of movement towards the normal. On the upper surface of the frame vertical constant loads are applied from the walls and overlapping (Figure 4), which, including the own weight of the frame, increase linearly from 1 (early June) to 3 (end of August) stage and remain unchanged in stage 5 (mid-January) (see Figure 2).

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To describe the process of destruction and cracking of concrete, the Willam-Warnke model was used, the final element of which in Ansys Mechanical is denoted Solid65. CE Solid65 is capable of cracking, crushing, plastic deformation and creep [8, 9, 10, 11].

Investigations of the influence of low temperatures on reinforced concrete structures are considered in [2, 12, 13, 14, 15, 16]. As a stress-strain diagram of compressed concrete, the nonlinear diagram proposed in [17, 16, 18] is adopted, which varies with a temperature change in the range from +20 °C to –60 °C and concrete humidity in the range from 4.05% to 4.9% (Figure 5). The stress-strain diagram of stretched concrete is assumed to be linear.

The change in humidity over time was not taken into account. The design in accordance with SP 52-105-2009 was conditionally divided into 2 groups, which have different working conditions due to different humidity of the concrete. The first group includes structures that are located above the 0.5 m mark above the surface of the ground, which are frozen and thawed in a normal moisture state (*W* = 4.05%), to the second group – structures that are below 0.5 m above the ground surface of the soil, which undergo alternate freezing and thawing in the water-saturated state (*W* = 4.9%).

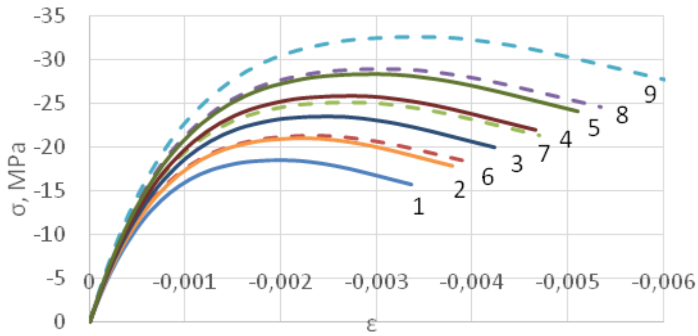

Figure 5. Stress-strain diagram of compressed concrete (*σ*-*ε*): 1 – at t = 20 °C and *W* = 4.05..4.9%; 2, 3, 4, 5 – at *W* = 4.05% and, respectively, *t* = 0, –20, –40, –60 °C; 6, 7, 8, 9 – at *W* = 4.9% and, respectively, *t* = 0, –20, –40, –60 °C;

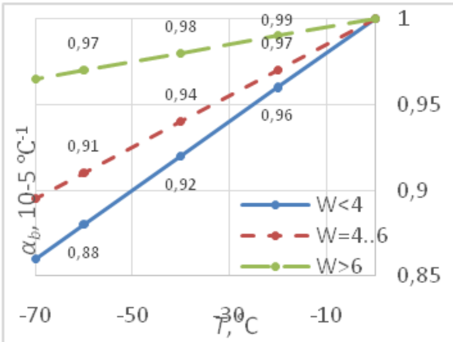

Figure 6. Coefficient of thermal expansion of concrete α_b

Coefficient of thermal expansion of concrete due to the developed system of internal pores and capillaries, in which processes that significantly change its properties occur during freezing, have a non-constant value. In this paper, the dependence of the coefficient of thermal expansion of concrete on the operating conditions (humidity) and freezing temperature, empirically derived in [12], is adopted. The graphs of the dependence of the coefficient of temperature expansion on humidity and freezing temperature for heavy concrete at water/cement = 0.4 are shown in Figure 6.

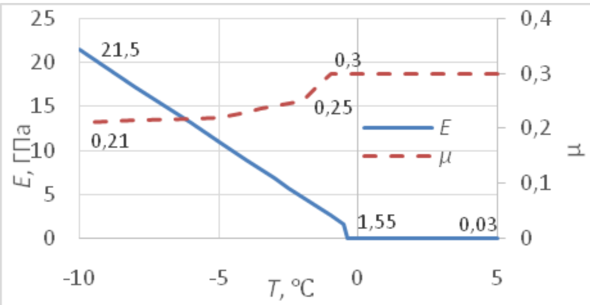

Figure 7. Modification of the elasticity modulus and Poisson's coefficient from temperature

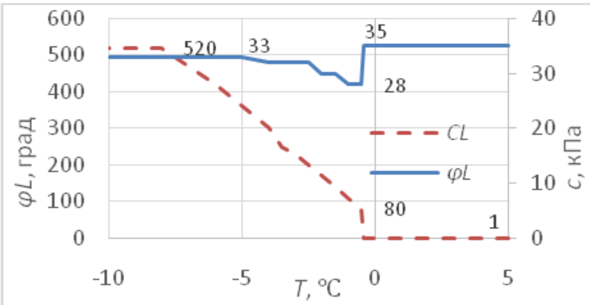

Figure 8. Change in the angle of internal friction and the specific friction of temperature

The behavior of the soil is modeled using the Mora-Coulomb model [19], which is based on the theory of plastic flow using an unassociated surface flow and begins to plastically deform when a combination of medium pressure and shear stress achieves cohesion of the material particles. Strength and deformation characteristics of the thawed soil are taken according to SP 22.13330.2011;

mechanical characteristics of frozen soil according to SP 25.13330.2012, and deformative according to [20] and [21]. The accepted mechanical characteristics of the soils are shown in Figures 7 and 8.

The results of the calculations show that under the action of only vertical loads, crack formation in the span part of the foundation beams is not observed, only normal cracks appear on the support zones (Figure 9). The pattern of crack formation changes sharply when thermal effects are applied - the cracks form along the entire length of the beams (Figure 14) - both normal and inclined, in addition, normal cracks appear in the upper part of the extreme pile. In this case, normal cracks are revealed throughout the section. This is due to the fact that, in addition to bending, the beam also works on stretching.

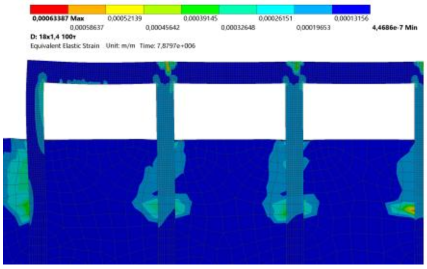

Figure 9. Equivalent elastic strain in stage 3 (100 tons per pile)

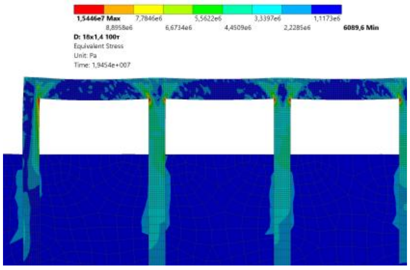

Figure 10. Equivalent stresses in stage 5 (100 tons per pile)

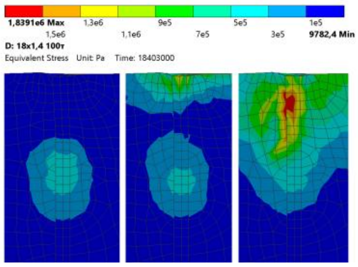

Figure 11. Equivalent stresses in the soil from the left to the right – 3, 4 and 5 stages (100 tons per pile)

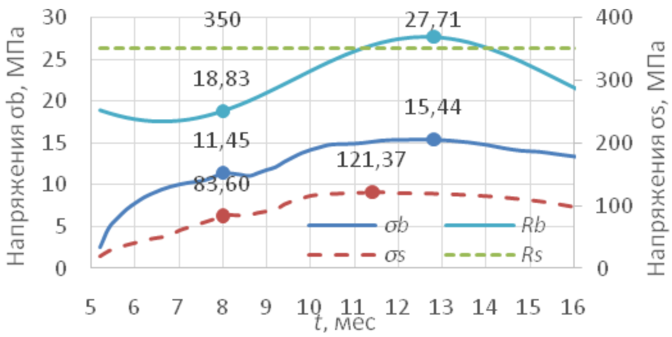

Figure 12. Time distribution of maximum equivalent stresses in concrete σ_b, stresses in upper longitudinal reinforcement σ_s, strength of compressed concrete R_b and reinforcement R_s

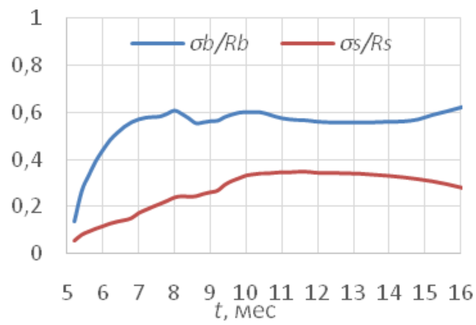

Figure 13. Coefficients of use of the bearing capacity of concrete σ_b/R_b and the reinforcement σ_s/R_s in time

Figure 11 shows equivalent ground stresses. As expected, with the ground freezing, the stresses begin to be distributed over the upper layers of the soil.

The results show that the temperature effects increase the maximum equivalent stresses in concrete caused by vertical loads by 34.85%, and the stresses in the reinforcement by 45.18% (Figure 12). The coefficient of use of the load-carrying capacity of concrete after full loading of a constant vertical load practically does not change (Figure 13). At the same time, a minimum safety factor is observed at the end of the 16th month (end of April). This is due to the fact that there is a temperature expansion, when the soil is in the frozen state, which loads the extreme pile.

The results of the analysis show the different nature of the stress-strain state of the foundation frame by a span of 18 m with vertical loads on piles 100, 50 and 0 tons (Figures 14–16). In the absence of a vertical load, a uniform distribution of cracks along the length of the piles and in the bearing zones of the foundation beams is observed. The greatest deformations are observed in the inner corner of the joint of the extreme pile with the foundation beam. When applying vertical loads of 50 and 100 tons, the cracks are mainly concentrated in the foundation beams, in the piles the cracks appear only at the junction in the foundation beam. This circumstance can be explained both by

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compressing the piles with vertical loads and by the appearance of moments of the opposite sign in piles from the temperature deformations of the foundation beam in comparison with the moments from vertical loads.

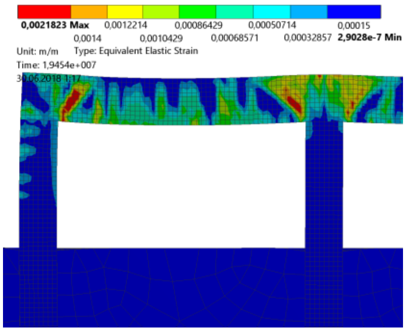

Figure 14. Equivalent elastic strain in stage 5 (100 tons per pile)

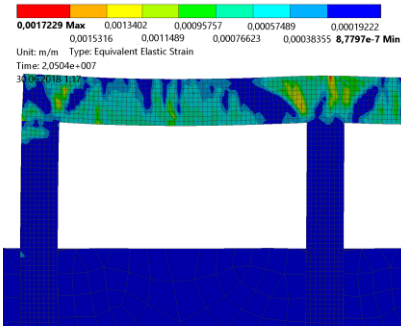

Figure 15. Equivalent elastic strain (50 tons per pile)

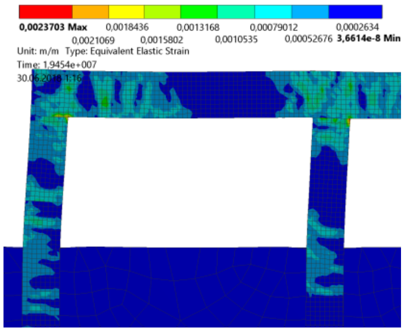

Figure 16. Equivalent elastic strain (0 tons per pile)

Conclusions

1. The temperature distribution over the depth of permafrost soils is obtained depending on the change in the outdoor air temperature, taking into account changes in physical properties, as well as heat release and heat absorption, associated with phase transitions of water.
2. Modeling and calculation of the foundation frame (foundation beams-piles) was performed taking into account the change in the deformative and strength characteristics of concrete and soil of different humidity for a nonstationary change in the outside air temperature, including thawing and freezing phases.
3. Temperature effects have a significant effect on stress-strain state. It is shown that the cracking of foundation structures is mainly due to temperature effects.
4. The nature of the crack formation depends on the magnitude of the vertical loads. As the crack values increase, they are more pronounced in the foundation beams, in the piles the cracks occur mainly in the absence of vertical loads.
5. For analysis of stress-strain state by analytical methods, it is necessary to develop a calculation technique with variable bed coefficient in time and depth depending on the soil temperature with consideration of several stages of pile work with soil.

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