Numerical studies of reinforced concrete pile foundations on permafrost soils at low climatic temperatures

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Abstract. In this manuscript, a finite-element analysis of the stress-strain state of the system “reinforced concrete pile foundation - permafrost soil” is carried out taking into account various conditions of concrete operation, unsteady changes in ambient temperature and the latent heat of phase change of permafrost. The effects of changes in the stress-strain curves of concrete and its coefficient of thermal expansion depending on low temperature on the stress-strain state of the pile foundation are analyzed.

1. Introduction
One of the significant factors affecting the durability of reinforced concrete structures operating in the Far North is low climatic temperatures. A survey of buildings in Yakutia (a federal Russian republic), where an absolute minimum temperature of -67.8 °C [1] was recorded, shows that unacceptable flexural and shear cracks are observed on the beams and piles. The formation of such cracks on the beams is observed even in the first winter period in buildings with only a foundation. These damages are caused by thermal deformations of structures devoid of free displacement [2, 3].

In Yakutia, mainly buildings are erected on pile foundations with ventilation under the buildings, which allows maintaining the frozen state of soils throughout the life of the building, but leaves the foundation structures unprotected from temperature influences.

An adequate analysis of the stress-strain state of such structures requires the calculation of the system “reinforced concrete pile foundation - permafrost”. The stress-strain state of such structures is significantly affected by the rigidity of the structure and the flexibility of the supports, which depend on the presence of cracks and low temperature. In this case, the physicomechanical properties of concrete and soil change significantly.

A significant factor in the calculation of reinforced concrete structures for temperature effects is the coefficient of thermal expansion (CTE) of concrete, which depends on its humidity and temperature.

This manuscript analyzes the effects of a nonlinear stress-strain curve of concrete under normal conditions, a differential nonlinear stress-strain curve of concrete, and differential CTE, depending on the low temperature, on the stress-strain state of a reinforced concrete pile foundation. As a result, four numerical models were calculated in which the indicated properties of concrete varied (table 1). Soil and reinforcement behaviors were the same for all models.
Table 1. Characteristics of models for comparison

| Concrete behavior | Coefficient of thermal expansion of concrete |
|-------------------|---------------------------------------------|
| 1 differential nonlinear stress-strain curve depending on temperature | Differential CTE depending on temperature |
| 2 nonlinear stress-strain curve | $1 \times 10^{-5}$ C$^{-1}$ |
| 3 differential nonlinear stress-strain curve depending on temperature | $1 \times 10^{-5}$ C$^{-1}$ |
| 4 elastic behavior | $1 \times 10^{-5}$ C$^{-1}$ |

2. Formulation of the problem

Place of construction – Yakutsk. The considered soil mass is $11.8 \times 2.6 \times 18$ m in size. In plan, the boundary of the soil mass is 2.6 m from the extreme pile axis. The design and reinforcement of the pile foundation are shown in Figure 1. For the calculation, 1/4 part is considered object, cut in the area of symmetry. The finite element model is shown in Figure 2. The number of finite elements in the model was 77722 pieces.

2.1. Boundary and initial conditions of thermal analysis

At the upper boundary of the soil mass, convective heat transfer with the ambient temperature is set, which is determined by the average monthly outdoor temperature $T_1(t)$ and heat transfer coefficient $\alpha$. The heat transfer coefficient between soil and air is adopted $\alpha = 10$ W/(m$^2$°C) (the surface of the earth is not covered by snow and vegetation);

To surfaces of the reinforced concrete frame, which are higher than 0.5 m above ground level, a temperature $T_2(t)$ different from the average monthly outdoor temperature $T_1(t)$ is set, since according to the Russian code SP 20.13330.2016, the calculated temperatures in absolute value exceed the average monthly temperatures.

The temperatures $T_1(t)$ and $T_2(t)$ are approximated by a cosine of the form:

$$T_{1,2}(t) = A \cdot \cos \frac{2\pi}{t_{\text{year}}} t - t_0 - B$$  \hspace{2cm} (1)

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

The soil temperature at the lower boundary is set according to thermometric data $T_0 = -2.9$ °C, and zero heat fluxes at the lateral surfaces. The initial temperature of the computational domain is taken equal to $T_0 = -2.9$ °C.

To stabilize the soil temperature, a thermal analysis was carried out for ten annual cycles.

2.2. Loading, boundary conditions, and interactions of structural analysis

The lateral surfaces of the model are constrained by displacements towards the normal. The contact of the pile with the ground is accepted bound. The temperature load imported from thermal analysis and corresponding to the time range from June 1 of the ninth year to June 30 of the tenth year from the beginning of the calculation is valid for the entire calculation period. On the upper surface of the frame, the dead weight of the frame and the loads from the walls and floors are applied, which increase linearly in the time range from June 1 to August 31 and then remain unchanged (building in the summer). The half-length of the triangular load diagram is 1.2 m, the largest point of the distributed load is 2.06 MPa, the smallest is 50 kPa. The dead weight of the soil was not taken into account in the calculation.
2.3. Material models
For the calculation, the following material properties are accepted: concrete grade according to GOST 2663-2012 is B25 (the compressive strength is 18.5 MPa, the tensile strength is 1.55 MPa and the elastic modulus is 30,000 MPa under normal conditions) and reinforcement grade according to GOST 5781-82 is A400 (yield strength is 400 MPa and elastic modulus is 206000 MPa)

2.4. Concrete model
To simulate the behavior of concrete, the Willam-Warnke model was used, whose finite element in Ansys Mechanical is denoted Solid65. The finite element Solid65 is capable of cracking, crushing, plastic deformation and creep [4, 5, 6, 7].

The effects of low temperatures on reinforced concrete structures were studied in manuscripts [8, 9, 10, 11, 12, 13]. Non-linear compressive curves of concrete are adopted according to the laws proposed in the works of N. I. Karpenko and S. N. Karpenko [14, 15, 16]. These laws take into account changes in the elastic modulus, tensile strength and ultimate deformation when the temperature changes in the range from +20 °C to −60 °C and concrete humidity in the range from 4.05% to 4.9% (Figure 3). The tensile stress-strain curves of concrete are accepted linear.

The change in humidity over time was not taken into account. The structural elements of the pile foundation in accordance with the Russian code SP 52-105-2009 were divided into two groups, which have different properties due to different humidity of concrete. The first group includes elements located above the level of 0.5 m above the soil surface, which are operated in the normal moisture state (W = 4.05%). The second group includes elements that are below the level of 0.5 m above the daily surface of the soil, which are operated in a water-saturated state (W = 4.9%).
The nonlinear compressive stress-strain curve of concrete for the second model corresponds to the curve under normal conditions: at $t = 20 \, ^{\circ}C$ and $W = 4.05\%$ (curve 1 in Figure 3).

Differential CTE ($\alpha_{bt}$) of concrete was adopted on the basis of [8], which proposed an empirical dependence of CTE of concrete on operating conditions (concrete moisture) and temperature:

$$\alpha_{bt} = \alpha_{bt,0} + 5 \times 10^{-9} n_w T,$$

where $\alpha_{bt}$ and $\alpha_{bt,0}$ are the coefficient of thermal expansion of concrete at under climatic temperatures below zero by Celsius and normal conditions, respectively, $\alpha_{bt,0} = 1 \times 10^{-5} \, ^{\circ}C^{-1}$; $n_w$ is an empirical coefficient depending on operating conditions (concrete moisture), $n_w = 4$ at $W < 4\%$, $n_w = 3$ at $4 \leq W \leq 6\%$, $n_w = 1$ at $W > 6\%$, $T$ is the freezing temperature of concrete, $^{\circ}C$.

2.5. Reinforcement model
The reinforcement was modeled using Beam 188 finite elements, which has flexural rigidity. Steel material is capable of bilinear kinematic hardening.

2.6. Ground model
The behavior of the soil is modeled using the Mohr-Coulomb model [17], which begins to plastically deform when the shear stress exceeds the internal friction resistance between the particles of the material. Strength and deformation characteristics of thawed soil are adopted according to the Russian code SP 22.13330.2011. The strength characteristics of frozen soil according to the Russian code SP 25.13330.2012, and the deformation characteristics of frozen soil according to the proposals of [18] and [19]. The accepted soil characteristics depending on temperature are shown in Figure 4.

2.7. Thermal analysis of soils taking into account phase changes
The thermal analysis of soils is calculated taking into account the latent heat of the phase changes of water, that is, heat energy that the system stores or releases during a phase change. For this, the enthalpy of the soil, which has units of heat/volume, is determined as a function of temperature according to the formulas the Russian code RSN 67-87:

for $u > u^*$.
\begin{equation}
H(u_0) = H_2 + \rho_d(C_d + W_{tot})(u_0 - u^*),
\end{equation}
for \(u^* \leq u_0\):
\begin{equation}
H(u_0) = \rho_d(C_d + 0.5(W_{tot} + M))(u^* - K) - A\rho_d[0.5\ln \left(\frac{u_0 - B}{K - B}\right) + \alpha \frac{K - u_0}{(K - B)(u_0 - B)}],
\end{equation}
where \(H_1, H_2\) are critical enthalpy values:
\begin{equation}
H_1 = \rho_d(C_d + 0.5(W_{tot} + M))(u^* - K) - A\rho_d[0.5\ln \left(\frac{u^* - B}{K - B}\right) + \alpha \frac{K - u^*}{(K - B)(u^* - B)}],
\end{equation}
\begin{equation}
H_2 = H_1 + \alpha\rho_d(W_{tot} - W_w(u^*)),
\end{equation}
\(K = -273.15\) °C is t absolute zero on the Celsius scale, at which the enthalpy is taken equal to zero, \(C_d\) is the specific heat of dry soil, \(\rho_d\) is the density of dry soil, \(\alpha\) is the latent heat of phase transitions, \(W_{tot}\) is the total soil moisture in fractions to the weight of absolutely dry soil, \(u_0\) is the temperature of the soil, \(u^*\) is the phase transition temperature, \(W_w\) is the fraction of unfrozen water at a temperature of \(u_0\), is taken in the form:
\begin{equation}
W_w(u_0) = A / (B - u_0) + M,
\end{equation}
where \(A, B, M\) are the coefficients defining the curve of unfrozen water for \(u_0 < u^*\).

ANSYS Mechanical uses the possibility of thermal analysis in the form of volume enthalpy:
\(H = \int \rho c(T) dT\). Enthalpy is a monotonically increasing function of temperature, which has a jump at the freezing point of groundwater [20] (Figure 5).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{enthalpy_frozen_soil}
\caption{Enthalpy and fraction of unfrozen water in the soil depending on temperature}
\end{figure}

2.8. Analysis settings

In the settings of the transient thermal analysis, auto time stepping was used with the minimum and maximum time steps of 86400 and 345600 sec, respectively.

For the nonlinear formulation of transient thermal analysis, the full Newton-Raphson method with thermal convergence is used. The tolerance value of the heat convergence of the iteration process is assumed to be 2% in the time range from mid-September to the end of October, since significant phase transitions occur at this time, and the remaining tolerance is 0.5%.

The calculation time was 7 hours, and the number of iterations was 4401.

It should be noted that in the earlier work [21], the latent heat of phase transitions was taken into account by introducing the effective heat capacity [22, 23, 24]. With this approach, in the temperature range of phase transitions, there is a sharp change in the specific heat, which impairs convergence.

For structural analysis, we also used auto time stepping with the minimum and maximum number of steps 50 and 200, respectively, and automatic correction of the convergence criterion. The tolerance of force convergence of the iteration process is 0.5%. To solve the system of linear equations, the Preconditioned Conjugate Gradient method is used. The asymmetric Newton-Raphson solver is used.
The maximum equivalent plastic strain allowed within a substep is 50%. The calculation time in four models averaged 20 minutes, and the number of iterations was 56.

3. Results
The results of the thermal analysis of soils are shown in Figures 6 and 7. The temperature at a depth of 10 m has shifted from the initial –2.9 °C to –5.8 °C. Figure 7 shows how, in the temperature range of phase transitions, the accumulation or release of heat is manifested, and the temperature change slows down.

Figures 8 and 9 show the maximum equivalent (von Mises) stresses, the maximum and minimum combined reinforcement stresses, and the maximum beam deflections.

![Figure 6](image6.png)
**Figure 6.** The temperature regime of the soil by month (the numbers show the month, the lines show the temperature in the soil, the points show the ambient temperature)

![Figure 7](image7.png)
**Figure 7.** Change in the average monthly ambient temperature $T_1(t)$, the calculated temperature effect on the pile foundation $T_2(t)$, soil temperature at a depth of -0.5 m (A), -2 m (B), -4 (C), -6 m (D).

![Figure 8](image8.png)
**Figure 8.** a) Maximum equivalent (von Mises) stresses of concrete; b) maximum combined stresses of reinforcement: 1, 2, 3, 4 – model numbers (table 1)
The locations of the maximum and minimum values vary depending on the load. To study the results of the models, the values at the minimum ambient temperature are considered. The locations of the maximum and minimum values of which are shown in Figures 10–11.

The results of a structural analysis of the pile foundation show that when calculating the nonlinear stress-strain curve of concrete, the maximum equivalent stresses in concrete decrease by 54.76% compared to the model with elastic behavior of concrete, and the deflections increase by 36.09%.

Calculation taking into account the differential nonlinear compressive stress-strain curve of concrete as compared with the model with the non-differential curve increases the maximum equivalent stresses in concrete and the maximum combined stresses in reinforcement by 26.14% and 4.04%, respectively, and reduces the minimum combined stresses in reinforcement and deflections by 6.83% and 5.99%, respectively.

The use of differential CTE of concrete reduces the equivalent stresses in concrete and the maximum combined stresses in reinforcement by 20.72% and 30.33%, respectively, and increases the minimum combined stresses in reinforcement by 49.16%. In this case, the deflections of the beam practically do not change.
Significant changes in stresses are associated with the cracking pattern in the reinforced concrete structure of the pile foundation. When the CTE of concrete is $1 \times 10^{-6}$, cracks appear on the extreme pile at ground level (Figure 11 b, c), which reduces the rigidity of the pile, thereby increasing the compliance of the supports. With differential CTE, i.e. decreasing CTE with decreasing temperature, cracks are more developed in the frame beam (Figure 11 a).

It should be noted that cracks are mainly caused by thermal forces arising in the calculated frame at low temperature.

![Figure 11](image)

**Figure 11.** Equivalent (von Mises) strains for the a) first, b) second, c) third models (table 1); reinforcement stresses for the d) first, e) second, f) third models (table 1)

4. Conclusion

In this manuscript, a finite-element analysis of the stress-strain state of the system “reinforced concrete pile foundation - permafrost soil” is carried out taking into account various conditions of concrete operation, unsteady changes in ambient temperature and the latent heat of phase change of permafrost, and the effects of changes in the stress-strain curves of concrete and its coefficient of thermal expansion depending on low temperature on the stress-strain state of the pile foundation are analyzed.

Based on numerical analysis, the following conclusions are drawn:

The deflection of the reinforced concrete pile foundation under low temperature loading is most affected by the consideration of the nonlinear stress-strain curve of concrete. In models where nonlinearity was taken into account, the deflections were 4.509 – 4.799 mm, and in models with the
elastic behavior of concrete it was 3.512 mm. Taking into account changes in the elastic modulus from temperature increased displacements by 5.99%.

The stress-strain state of a reinforced concrete pile foundation on permafrost soils is significantly affected by the cracking pattern. So, in the model where differential CTE is taken into account, cracks mainly appear in the frame beam, and in the models with CTE equal to $1 \times 10^{-5}$ °C$^{-1}$ they appear on the pile at the level of the soil surface, which increases the compliance of the pile and changes the stress-strain state of the structure. The maximum equivalent stresses in concrete changed by 20.72%, and the maximum and minimum combined stresses in reinforcement by 30.33% and 49.16%, respectively.

In the numerical model, where the non-linear curve and changes in the physicomechanical properties of concrete from low temperature were not taken into account, the stress-strain state differs significantly from the model in which these properties were taken into account. So, the maximum equivalent stresses in concrete showed a 110% higher value, and the maximum combined stresses, minimum combined stresses in reinforcement and beam deflections showed 43.15, 45.44 and 22.88% less, respectively.

Thus, in order to adequately determine the stress-strain state of the system “reinforced concrete pile foundation - permafrost soil” under climatic temperature loads, it is necessary to take into account the changes in the physicomechanical properties of concrete from low temperature, the non-linear stress-strain curve of concrete and reinforcement, as well as the collaboration of piles with permafrost, for which it is required to take into account the latent heat of phase transitions and changes in the physicomechanical properties of permafrost.

Also, the stress-strain state of such systems can be affected by such phenomena as frost heaving, moisture migration, a change in the heat transfer coefficient between soil and ambient temperature depending on the time of year, and stratification of the contact between the pile and permafrost, which are not considered in this paper.

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