Mathematical modeling technology of a foundation slab concreting on a frozen base

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Abstract. The current regulations prohibit to concretebuildings sights on a base with low temperature. The base warming is a long and energy-intensive process. The substantiation of concreting technology was carried out to concrete the foundation slab at an air temperature of 20°C on a frozen base. The first stage was the use of mathematical method modeling for the feasibility of a base heating. After making sure that the heating had been inefficient, the possible to provide favorable temperature holding conditions due to the heat release of the cement, compensating for heat loss through the side faces of the slab or by the concrete heating on contact with the base and on the exposed surface was estimated. Mathematical modeling, confirmed by the results of real concreting, allowed to determine the technology of heat treatment, which provided the necessary quality of concrete, hardened on a frozen base.

Key wads: modeling technology, foundation slab, frozen base, surface, heat release of the cement

1. Introduction

Winter conditions in the concrete works production in Siberia, in the edition of SP 70. 13330.2012. [1. p.5.11.1], last from 5 to 8 months in a year. This leads to a significant rise in the construction cost. Norms [1, paragraph 5.3.3] directly indicate the need to ensure the base temperature in the process of a concrete mixture laying at least 5°C. This means that the frozen base needs to be heated before the concrete laying, or to offer a method of laying that will prevent the possibility of concrete mixture freezing in the contact zone with the base [1, item 5.11.4].

In the winter construction 2017-18 seasons, in the process of the foundation slab concreting in the closed parking lot at Fabrichnaya Street in Novosibirsk, the construction company NTBild LLC was faced with the need to lay concrete on the frozen foundation. Up to the beginning of the slab concreting, in autumn 2017, according to the project, at the excavation bottom, a layer-by-layer cushion compacted sand of medium size with 300 mm thickness and a concrete preparation on a compacted base of B 7.5 class with a thickness of 100 mm were made. With the beginning of winter, site's construction work was stopped. The pit was filled with snow, which worked as a heater in the future. In February 2018, it was decided to continue work. The depth of ground freezing in the base, determined after snow removal by pilot drilling, was 500 mm. The work was scheduled for 01.03.2018. At the expected minimum daily temperature in Novosibirsk -20°C, the foundation plate with dimensions of 47100 × 19200 mm and a thickness of 500 mm was to be concreted, using the concrete grade of B20 F75 W6 plate with cement consumption of PC 400 - 400 kg/m^3. Heat treatment of concrete was assumed to be a heating wire fixed to the upper and lower reinforcing mesh.

The substantiation of a slab concreting technology was carried out in two stages.

1. Estimation of energy inputs and base heating time.

2. Evaluation of temperature conditions and strength of concrete foundation plate subjected to a wire heat treatment in various combinations of its location.

2. Heated base

According to environmental requirements, the ground heating in the urban area by coal massif burning on the surface is strictly forbidden. In addition, an open fire on the surface of the frozen concrete can lead to its destruction. The only possible way to warm the base remains heating with a heating wire or thermo-mats [2-4]. The slab area is about 900 m^2. It is rather problematic to collect such a number of mats even within the concreting into 2 captures. Therefore, preliminary there was evaluation of the ground heating with the use of the heating wire or cable under a dry sand layer.

Physical formulation of the problem. In accordance with the design scheme (Fig. 1), the heating wire is laid on the surface of concrete preparation with step *b* and covered with a sand layer padding of δ_n thickness. In order to ensure the uniformity of the temperature field at the base, the maximum pitch of the heating wire is $b_{\max}$=250 mm. To simplify the calculations, fine concrete preparation and sandy pouring, considering the proximity of their thermophysical characteristics and small dimensions, can be included in the calculation scheme with a single layer of frozen soil. At the time the heating cable is turned on, the temperature of the sandy substrate is assumed to be equal to the temperature Θ.

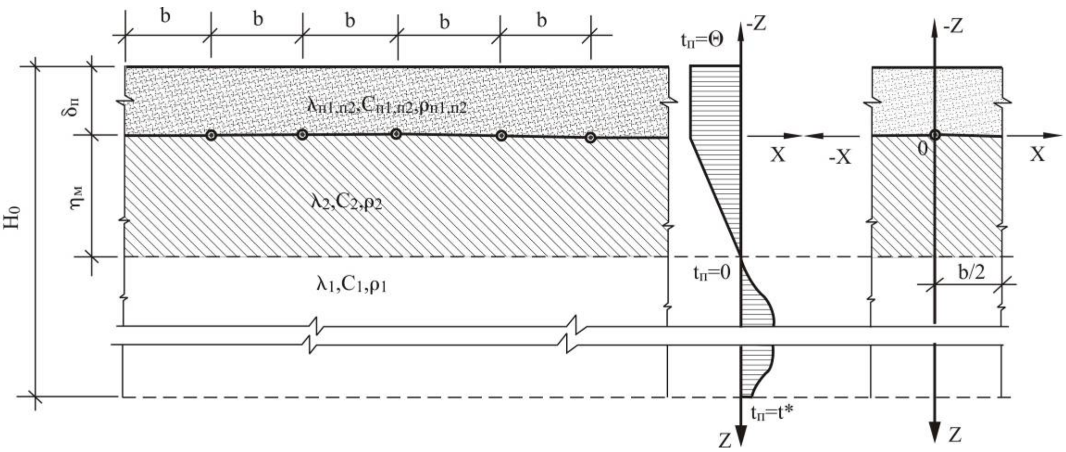

Figure 1. Calculation scheme for thawing and warming up the soil base of the pit under the slab foundation.

The freezing boundary of the unbound base ($\eta_м$) is clearly fixed by the plane of phase transitions [5-8]. Physicomechanical and thermophysical characteristics: sandy priming: λ_{n2}, C_{n2}, ρ_{n2}– in the frozen state and λ_{n1}, C_{n1}, ρ_{n1} - in the melted state; the characteristics of the base: the foundation soil, the priming and the concrete: respectively λ_2, C_2, ρ_2 и λ_1, C_1, ρ_1 with the moisture components (in fractions of unityω_{nsv} and ω_{sv}, due to the amount of unfrozen, respectively, unbound and bound moisture. The heating wire of the PNSV brand with a 1.2 mm steel core diameter allows providing a heat output of 8.9 w/m.

The mathematical formalization of the physical model has the form:

$$1.\ \frac{\partial t_{n1,n2}}{\partial \tau} = \frac{\lambda_{n1,n2}}{C_{n1,n2}} \left[\frac{\partial^2 t_{n1,n2}}{\partial x^2} + \frac{\partial^2 t_{n1,n2}}{\partial z^2} \right], x \in \left(\frac{b}{2} \right) \wedge z \in \left(-\delta_n \right)$$

$$2.\ \frac{\partial t_{1,2}}{\partial \tau}=\frac{\lambda_{1,2}}{C_{1,2}}\left[\frac{\partial^2 t_{1,2}}{\partial x^2}+\frac{\partial^2 t_{1,2}}{\partial z^2}\right]\pm\frac{W_{\phi}(\tau)}{C_{1,2}},x\in\left(\frac{b}{2}\right)\wedge z\in H_0$$

$$3.-\lambda_{n1,n2}\frac{\partial t_{n1,n2}(z=-\delta)}{\partial z}=\alpha\left[t_{n1,n2}(z=-\delta)-\Theta\right]$$

$$4.-\lambda_{n1,n2,1,2}\frac{\partial t_{n1,n2,1,2}(z=\eta(\tau))}{\partial z}+\lambda_{n2,n1,2,1}\frac{\partial t_{n2,n1,2,1}(z=\eta(\tau))}{\partial z}= \\ =\varepsilon\omega_{нсв}\cdot\rho_{n1(n2),1(2)}\frac{\partial\eta}{\partial z} \qquad (1)$$

$$5.-\lambda_{n1,n2}\frac{\partial t_{n1,n2}\left(z=-\delta_n\right)}{\partial z}+\lambda_{1,2}\frac{\partial t_{1,2}\left(z=-\delta_n\right)}{\partial z}=q_{\omega_{ГЕК}}$$

$$6.\ t_1\left(x,z=H_0,\tau\right)=\text{const}=t^*$$

$$7.\ \frac{\partial t_{n1,n2,1,2}(x=0\vee x=b/2)}{\partial x}=0$$

$$8.\ t_{n2,1,2}(x,\tau=0)=\psi(z)$$

where 1.1 is the differential equation of the thermal conductivity of the sandy priming; 1.2 is differential equation of the thermal conductivity of cohesive soil, sandy priming and the base with a volumetric-distributed source of phase type heat; 1.3 is PG III kind on the surface of sandy priming; 1.4 is GU Stefan on the boundary of freezing (thawing) of unbound moisture; 1.5 is the thermal connection condition of the heating electrical cable to the sandy priming (from above) and to the ground of the base; 1.6 is PG of the first kind at the zero amplitude level of annual temperature variations; 1.7 is the thermal symmetry condition at the location of the cable core (x = 0) and at a distance b/2; 1.8 is the initial condition.

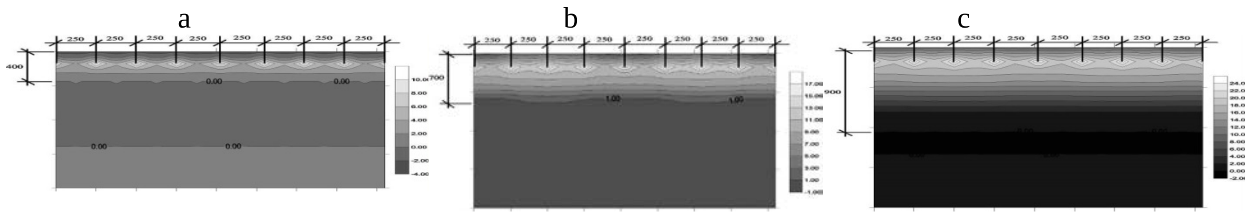

Figure 2. Temperature field of the base after a – 100, в– 200, c – 300 operating hours heaters. The horizontal chain sizes - step of laying the heating wire, vertical – depth base thawing.

Numerical implementation of the mathematical model. The dynamics of the change in the temperature field in the frozen ground mass after 100, 200 and 300 hours of the heaters operation is shown in Fig. 2.

It can be seen from the calculation results that at least 300 hours or 12.5 days will be needed to thaw the concrete, sandy priming and the frozen base. The decision is unacceptable in time and energy costs.

2.1. Temperature conditions and strength of concrete

Physical problem formulation. In accordance with the design scheme (Figure 3), the bottom of the pit was frozen to the depth *h* by the time of concreting. Estimated temperature Θ. Material of concrete and

Sandy priming managed to take the temperature of the ambient air. Peripheral heating of the plate can be carried out by electric heating wires with running heat q_l.

The intensity of the heat flux from the heating wires is determined by the formula

$$q_{\text{пр}} = \frac{q_l \cdot L}{1\,\text{m}^2}, \frac{\text{Wt}}{\text{m}^2} \quad (2)$$

where *L* is the length of the heating wire per 1 m^2 of the area.

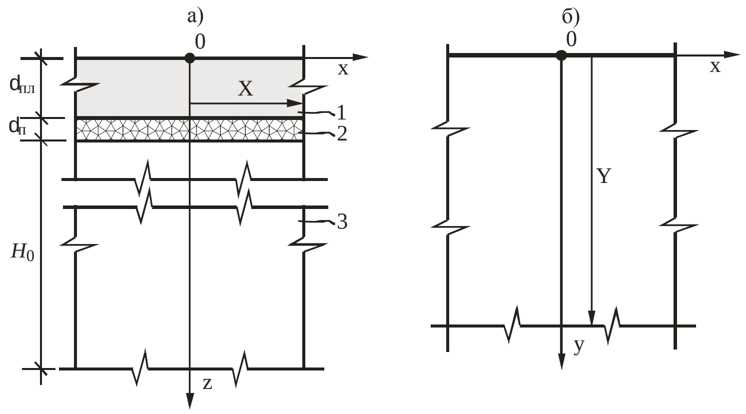

Figure 3. The calculated fragment of a concrete foundation slab: a) in a section; b) top view: 1 – foundation plate; 2 – concrete + sandy priming; 3 – foundation soil

With numerical realization of the differential equation of thermal conductivity of concrete foundation

$$Q_{\text{пр}} = \frac{q_{\text{пр}}}{C_{\text{б}} \cdot l}, \quad (3)$$

where *l* is the step of numerical integration along the axis normal to the vertical face in question.

Despite the fact that the foundation slab proposed for concreting refers to massive structures (M_n=0.47≤3 m^{-1}), where the volume-distributed heat source $\omega_{экз}$ plays a big role in the formation of the concrete temperature, it is necessary to verify the sufficiency of this source. If it is not enough, then you can implement warm-up methods:

- only the warming up process with electric heating wires of the side slab faces, which is concreted on the unheated soil base;
- heating the concrete of the slabs with electric heating wires at the level of the upper and lower reinforcing mesh and side faces.

In the process of a concrete mixture laying on a non-heated ground base, it is compulsory to make a computational confirmation that the concrete temperature at the contact with the concrete and sandy priming does not fall below 0 °C (for conventional concrete, without chemical additives) or below the freezing point of the mixing solution (concretes with antifreeze additives) .

The boundaries of the thermal influence zone of peripheral warming along the *Y* axis should be taken from the preliminary calculations from the $Y \geq 5\delta_{пл}$, condition of the boundary along the *X* axis should be taken from the condition $Y \geq 5\delta_{pl}$,, where *b* is the heating cable laying step. The lower boundary of the base calculation soil is at the point H_0, where the temperature *t** does not change during the year.

The mathematical formalization of the physical model has the form:

$$1.\ \frac{\partial t_{пл}(x,y,z,\tau)}{\partial\tau}=\frac{\lambda_{пл}}{C_{пл}}\left[\frac{\partial^2 t_{пл}(x,y,z,\tau)}{\partial x^2}+\frac{\partial^2 t_{пл}(x,y,z,\tau)}{\partial y^2}+\right.$$
$$\left.+\frac{\partial^2 t_{пл}(x,y,z,\tau)}{\partial z^2}\right]+W_{экз}+Q, x\in X\wedge y\in Y\wedge z\in\delta_{пл}\wedge\tau\in T$$

$$2.\ \frac{\partial t_{n1,n2}(x,y,z,\tau)}{\partial\tau}=\frac{\lambda_{n1,n2}}{C_{n1,n2}}\left[\frac{\partial^2 t_{n1,n2}(x,y,z,\tau)}{\partial x^2}+\frac{\partial^2 t_{n1,n2}(x,y,z,\tau)}{\partial y^2}+\right.$$
$$\left.+\frac{\partial^2 t_{n1,n2}(x,y,z,\tau)}{\partial z^2}\right], x\in X\wedge y\in Y\wedge z\in\left(\delta_{пл},\delta_{пл}+\delta_{n}\right)\wedge\tau\in T$$

$$3.\ \frac{\partial t_{1,2}(x,y,z,\tau)}{\partial\tau}=\frac{\lambda_{1,2}}{C_{1,2}}\left[\frac{\partial^2 t_{1,2}(x,y,z,\tau)}{\partial x^2}+\frac{\partial^2 t_{1,2}(x,y,z,\tau)}{\partial y^2}+\right.$$
$$\left.+\frac{\partial^2 t_{1,2}(x,y,z,\tau)}{\partial z^2}\right]\pm W_{ф}, x\in X\wedge y\in Y\wedge z\in\left(\delta_{пл}+\delta_{n},\delta_{пл}+\delta_{n}+H_0\right)$$

$$4.\ -\lambda_{пл}\frac{\partial t_{пл}(x,y,z=0,\tau)}{\partial z}=K_{пр1}\left[t_{пл}(x,y,z=0,\tau)-\Theta\right]$$

$$5.\ -\lambda_{пл}\frac{\partial t_{пл}(x,y=0,z,\tau)}{\partial y}=K_{пр2}\left[t_{пл}(x,y=0,z,\tau)-\Theta\right] \qquad (4)$$

$$6.\ -\lambda_{пл}\frac{\partial t_{пл}\left(x,y,z=\delta_{пл},\tau\right)}{\partial z}=\lambda_{n1,n2}\frac{\partial t_{n1,n2}\left(x,y,z=\delta_{пл},\tau\right)}{\partial z}$$

$$7.\ -\lambda_{n1,n2}\frac{\partial t_{n1,n2}\left(x,y,z=\delta_{пл}+\delta_{n},\tau\right)}{\partial z}=\lambda_{1,2}\frac{\partial t_{1,2}\left(x,y,z=\delta_{пл}+\delta_{n},\tau\right)}{\partial z}$$

$$8.\ -\lambda_{n1,n2,1,2}\frac{\partial t_{n1,n2,1,2}(z=\eta(\tau))}{\partial z}-\lambda_{n2,n1,2,1}\frac{\partial t_{n2,n1,2,1}(z=\eta(\tau))}{\partial z}=$$
$$=\varepsilon\omega_{нсв}\cdot\rho_{n1,n2,1,2}\frac{\partial\eta(\tau)}{\partial z}$$

$$9.\ t_1\left(x,y,z=\delta_{пл}+\delta_{n}+H_0,\tau\right)=\mathrm{const}=t^*$$

$$10.\ t_{пл}(x,y,z,\tau=0)=t_{бс}$$

$$11.\ t_{n2}\left(x,y,z\in\left(\delta_{пл},\delta_{n}+\delta_{пл}\right),\tau=0\right)=\Theta\wedge$$
$$\wedge t_{1,2}\left(x,y,z\in\left(\delta_{n}+\delta_{пл},\delta_{n}+\delta_{пл}+H_{0}\right),\tau=0\right)=\psi(z)$$

where 4.1 is the three-dimensional differential equation of the concrete thermal conductivity of a foundation slab with a volumetric-distributed heat source: exothermic (W_{ex}) type, acting throughout the concrete entire thickness ($x\in X\wedge y\in Y\wedge z\in\delta_{pl}$) and an artificial heat source Q_{pr} with fixation of its area actions for numerical approximation of the equation; 4.2 is three-dimensional differential equation of concrete thermal conductivity and sandy priming; 4.3 is three-dimensional differential equation of the base soil thermal conductivity with a volumetric-distributed heat source of phase type: W_f at $t_2\in(0\div5$ °C) $\wedge W_f = 0$ at $t_{2(1)}>0$ °C$\wedge t_2<–5$ °C; the action of the source (sink) $W_f\neq0$ is due to the freezing (thawing) of the bound moisture in the temperature range $t_2\in(0\div5$ °C); 4.4 is PG III kind on the surface of the plate (allows for any insulation of open surfaces to be taken into account); 4.5 is PG III kind on the vertical edge of the plate; 4.6 is PG IV kind (the condition of thermal slab abutment to the concrete and sand priming); 4.7 is PG IV kind (the condition of sandy priming thermal contiguity to the foundation bottom); 4.8 is classical GU Stefan on the boundary of freezing (thawing) and unbound moisture; 3.13.9 is PG of the first kind at the zero amplitude depth of the soil temperature annual variations; 4.10 is initial condition for a concrete slab; 4.11 is initial condition for the basis. In order not to clutter up the article with mathematical transformations for the convenience of the reader, the numerical realization of the mathematical model is not given in the article.

Numerical implementation of the mathematical model. As it was already noted, in the case of expensive heating, it is more appropriate to use heating wires [9-15] Considering the massiveness and powerful heat release of cement, we calculate the most economical option: only peripheral heating of the concrete laid vertical faces on the unheated soil base, to compensate for heat losses through the side formwork and insulation and vapor barrier of exposed surfaces. On top of the heater in the form of a sawdust layer, K_{ym} =6 0.9 W / (m^2·K), on the vertical faces of uninsulated plywood formwork, K_{on} = 6 W / (m^2·K). The concrete mixture is laid with a temperature of t_{bs} = 7°C. Only the side faces of the slab are heat treated. The calculated air temperature is Θ = -20°C. The temperature fields in the slab concrete at the moment of the end of its aging, the average temperature change of the concrete temperature in time, as well as the temperature of the concrete at the contact with the concrete and sandy pouring, is shown in Fig. 4. Concrete did not score critical strength in the contact zone.

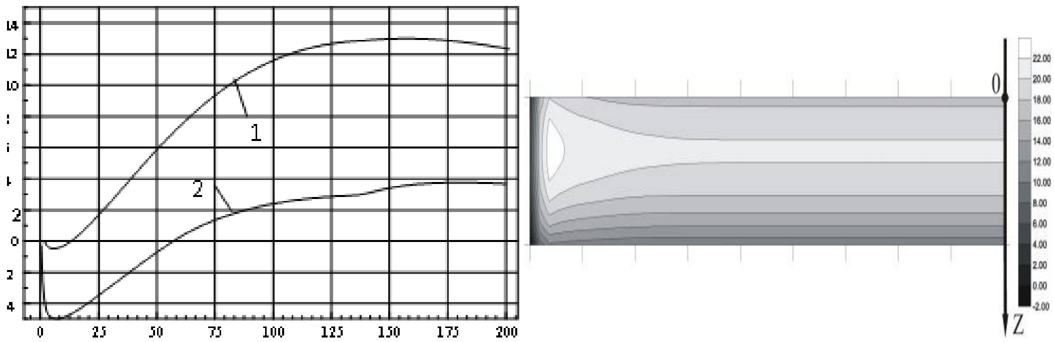

Figure 4. Results of calculations for concrete peripheral warming on the unheated soilbasis. 1 – volume-weighted average temperature of concrete according to calculations; 2 – concrete temperature in the place where it joins the sandy priming.

As can be seen from the forecast, the concrete loses its temperature at the boundary with the frozen surface after laying sharply, but at the expense of exothermal it quickly restores the average volume, but on the contact with the base it freezes at an early age and remains in the zone of negative temperatures for a long time, which can not but affect its quality. After 200 hours the average volume strength will reach 65 ÷ 70 % of the branded strength. However, the border zone is in danger.

In order to ensure the normal hardening of concrete and the acquisition of guaranteed strength, we calculate the more energy-intensive option. It is heating the concrete slab with electric heating wires at the level of the upper and lower reinforcement grids and peripheral heating of the vertical faces of the concrete laid on the unheated soil base (Fig. 5). The received intensity of internal heating by heating wires has been accepted equal: on the top reinforcement grid of 65 W/m^2 and on the bottom reinforcing grid 200 W/m^2. The time of critical strength concrete set was 75 hours, and the maximum temperature of concrete was 45°C.

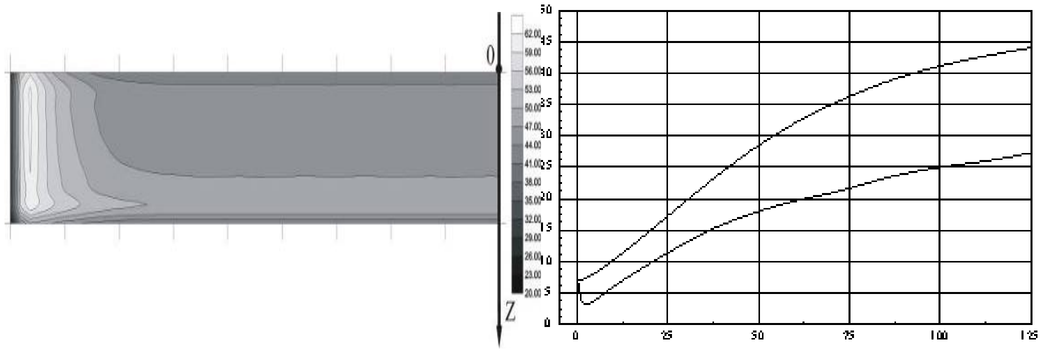

Figure 5. Concrete peripheral warming in combination with its heating at the level of the upper and lower reinforcement grids on the unheated soil base: 1 – weight-averaged volume of concrete temperature; 2 – temperature of concrete in the place where it joins the sandy priming.

3. Results

As a result of these studies it is argued:

- for thawing the base with a heating wire on a sand layer it will take 12.5 days, which is completely unacceptable;
- foundation plate thickness of 0.5 m in the process of concrete laying on a cold base, including 0.1 m of concrete preparation, 0.3 m of sandy soil and 0.5 m of frozen ground, due to intensive accumulation of heat, the base rapidly loses temperature and exothermic heat is clearly not enough to compensate for heat losses and conditions ensuring the purchase of concrete on contact with the base of the required strength;
- Calculations show the need for an additional heat source of 65 W/m^2 on the upper and 200 W/m^2 on the lower reinforcing mesh, which, together with heating of slab sides, ensures the purchase of concrete with specified strength.

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