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SIMPLIFIED MODEL FOR DETERMINING THE STRESS-STRAIN STATE IN MASSIVE MONOLITHIC FOUNDATION SLABS DURING CONSTRUCTION

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Abstract. The article proposes the simplified method for determining stresses in massive monolithic foundation slabs arising from the heat release of concrete during the hardening process. The proposed technique makes it possible to reduce a three-dimensional problem to a one-dimensional one based on the features of the distribution of stresses and strains in the structures under consideration, identified during finite element modeling in a three-dimensional setting. The resulting resolving equations take into account the creep and shrinkage of concrete, the coefficient of reinforcement of the structure. The strength and deformation characteristics of concrete are assumed as functions of the degree of maturity of the concrete, which in turn is determined by the time and temperature of curing. Approbation of the developed model is carried out by comparison with the calculation in a three-dimensional setting in the ANSYS software package. The influence of creep and contraction shrinkage of concrete, the degree of concrete maturity and the coefficient of reinforcement on the stress-strain state of structures is investigated.

Keywords: thermal stresses, massive monolithic structures, foundation slab, reinforced concrete, creep, shrinkage

УПРОЩЕННАЯ МОДЕЛЬ ОПРЕДЕЛЕНИЯ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ В МАССИВНЫХ МОНОЛИТНЫХ ФУНДАМЕНТНЫХ ПЛИТАХ В ПРОЦЕССЕ ВОЗВЕДЕНИЯ

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Аннотация. В статье предлагается упрощенная методика определения напряжений в массивных монолитных фундаментных плитах, возникающих вследствие тепловыделения бетона в процессе твердения. Предлагаемая методика позволяет свести трехмерную задачу к одномерной на основе особенностей распределения напряжений и деформаций в рассматриваемых конструкциях, выявленных при конечно-элементном моделировании в трехмерной постановке. В полученных разрешающих уравнениях учитывается ползучесть и усадка бетона, коэффициент армирования конструкции. Прочностные и деформативные характеристики бетона принимаются функциями от степени зрелости бетона, которая в свою очередь определяется временем и температурой твердения. Выполняется апробация разработанной модели путем сравнения с расчетом в трехмерной постановке в программном комплексе ANSYS. Исследуется влияние ползучести и контракционной усадки бетона, степени зрелости бетона и коэффициента армирования на напряженно-деформированное состояние конструкций.

Ключевые слова: температурные напряжения, массивные монолитные конструкции, фундаментная плита, железобетон, ползучесть, усадка

INTRODUCTION

For massive monolithic structures, which include foundation slabs, the problem of early cracking at the construction stage is relevant. This problem primarily arises because of uneven heating of structures, which in turn is due to the internal heat release of concrete during hardening and heat exchange with the environment [1-4].

Predicting the risk of early cracking is possible using computer simulation methods.

When modeling rectangular in plane massive foundation slabs, as a rule, a quarter of the structure is considered together with the soil massif [5] (Fig. 1).

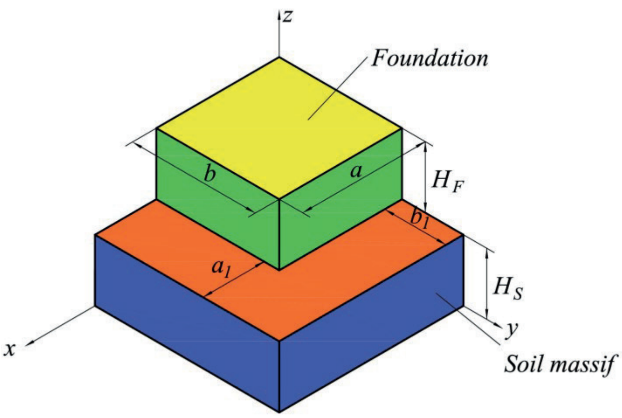

Figure 1. Calculation scheme of the foundation

The temperature field is determined from the solution of the differential equation of heat conduction [6]:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q=\rho c\frac{\partial T}{\partial t}, \tag{1}$$

where λ is the coefficient of thermal conductivity, T is the temperature, Q is the density of internal heat sources (W/m^3), ρ is the material density, c is the specific heat, t is the time.

In the presence of convective heat exchange with the environment (on the upper and side surfaces of the foundation, the upper surface of the soil), the boundary conditions are written as:

$$\lambda\frac{\partial T}{\partial n}+h\left(T-T_\infty\right)=0, \tag{2}$$

where n is the surface normal, h is the heat transfer coefficient, T_∞ is the ambient temperature.

On the side surfaces of the soil mass at a sufficient distance from the foundation, the temperature can be considered given:

$$T_g\left(t\right)=f\left(t\right). \tag{3}$$

The thermal conductivity coefficient and the specific heat capacity of concrete in equation (1) are generally functions of time. However, this factor cannot be taken into account in existing software systems (ANSYS, Abaqus, etc.)

According to [7], the thermal conductivity coefficient λ is the function of the hydration degree ξ:

$$\lambda\left(\xi\right)=\lambda_\infty\left(1.33-0.33\xi\right). \tag{4}$$

The hydration degree is determined from the differential equation [8]:

$$\frac{\partial\xi}{\partial t}=f\left(\xi\right)\exp\left(-\frac{E_a}{RT}\right), \tag{5}$$

where E_a is the activation energy, R is the universal gas constant.

For the function $f(\xi)$, the empirical formula can be used [8]:

$$f\left(\xi\right)=\frac{m}{n_0}\left(\frac{A}{m\xi_\infty}+\xi\right)\left(\xi_\infty-\xi\right)\exp\left(-\frac{\bar{n}\xi}{\xi_\infty}\right), \tag{6}$$

Here A_0, m, n_0 and $\bar{n}$ are the material constants depending on the type of cement.

When modeling the stress-strain state, it is necessary to take into account the dependence of the strength and deformation characteristics of concrete on time. One of the few authors that take this factor into account is T.C. Nguyen [9-

11]. For the elastic modulus, an explicit dependence on time is taken in the form

$$E(t) = E_0(1 - e^{-at}). \quad (7)$$

Formula (6) is not the only option for describing the dependence of the elastic modulus on time. Some other formulas can be found, for example, in [12, 13].

However, this approach is rather simplified, since the physical and mechanical characteristics of concrete at each point depend not only on the hardening time, but also on the history of temperature changes over time. More perfect is the concept of expressing the physical and mechanical characteristics of concrete through the degree of its maturity DM [14], determined by the integral:

$$DM(t) = \int_0^t T(\tau)\,d\tau. \quad (8)$$

The ultimate compressive strength of concrete at time t can be determined by the empirical formula [15]:

$$R_b = R_{28}\exp(0.35\left(1 - \left(\frac{15800 - 122.5\bar{T}}{\bar{T}t}\right)^{0.55}\right)) \quad (9),$$

where R_{28} is the strength of concrete at the age of 28 days (MPa), $\bar{T} = DM/t$, t is the age of concrete in hours.

The elastic modulus of concrete E (MPa) at time t can be represented as a function of the compressive strength R_b at time t [16]:

$$E = 1000\frac{0.04R_b + 57}{1 + \dfrac{29}{3.8 + 0.8R_b}}. \quad (10)$$

Accounting for the degree of maturity of concrete by standard means of the existing finite element software is also very difficult. In addition, since the temperature is different at each point of the structure, the modulus of elasticity becomes a function not only of time, but also of coordinates. Thus, the problem of the mechanics of an inhomogeneous body takes place.

In addition to taking into account the dependence of material characteristics on time, the determination of the stress-strain state of massive monolithic structures in the process of erection requires taking into account creep deformations and contraction shrinkage.

The purpose of this work is to develop a methodology for calculating the stress-strain state of massive monolithic foundation slabs in the process of construction, taking into account the above factors. A simplified technique is proposed, which, based on the characteristic features of the stress-strain state, makes it possible to reduce a three-dimensional problem to a one-dimensional one.

DERIVATION OF THE RESOLVING EQUATIONS

Finite element modeling of the temperature field in a three-dimensional formulation shows that for massive foundation slabs, with the exception of the edges, the temperature distribution is one-dimensional, i.e. the temperature does not depend on the x, y coordinates, and is a function of the z coordinate only. (Fig. 2)

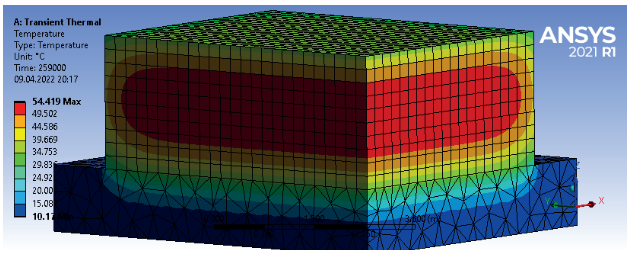

Figure 2. Temperature distribution in the foundation slab due to internal heat release of concrete during construction

Simulation of the stress-strain state in a three-dimensional setting shows that, with the exception of the edges, the stresses σ_z, τ_{xz}, τ_{xy}

and τ_{yz} are close to zero, and the stresses σ_x and σ_y are approximately equal to each other, even if the sides of the foundation are not equal to each other (Fig. 3-7).

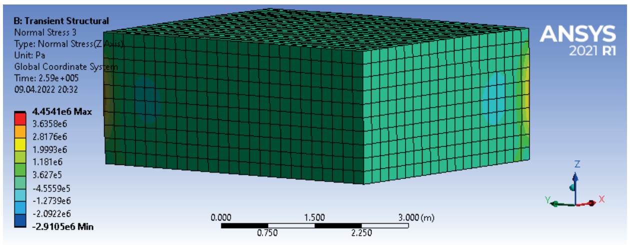

Figure 3. Stress σ_z distribution

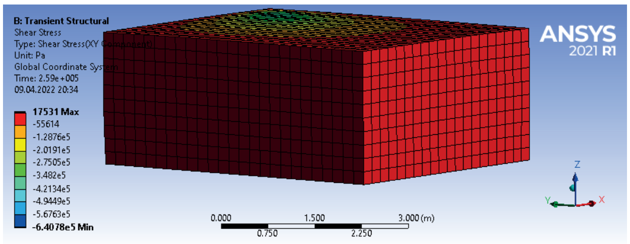

Figure 4. Stress τ_{xy} distribution

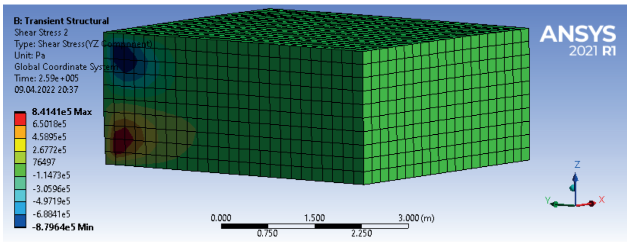

Figure 5. Stress τ_{yz} distribution

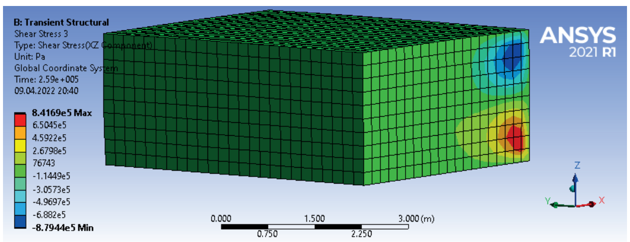

Figure 6. Stress τ_{xz} distribution

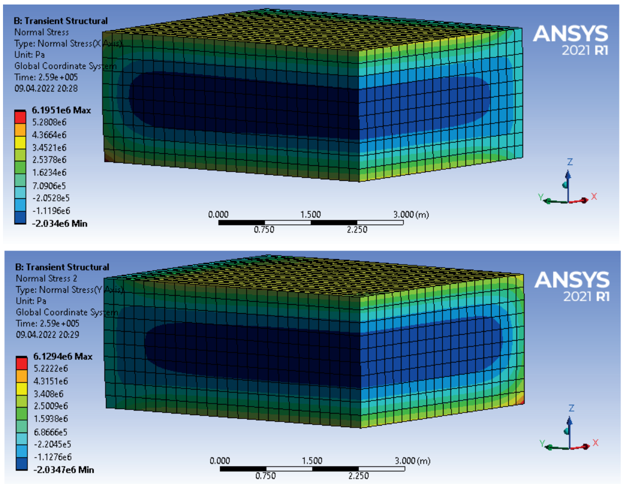

Figure 7. Stress distribution for σ_x (top) and σ_y (bottom)

Total deformations ε_x and ε_y, with the exception of the edges, are almost constant throughout the thickness of the slab, equal to each other and do not depend on the coordinates *x* and *y* (Fig. 8)

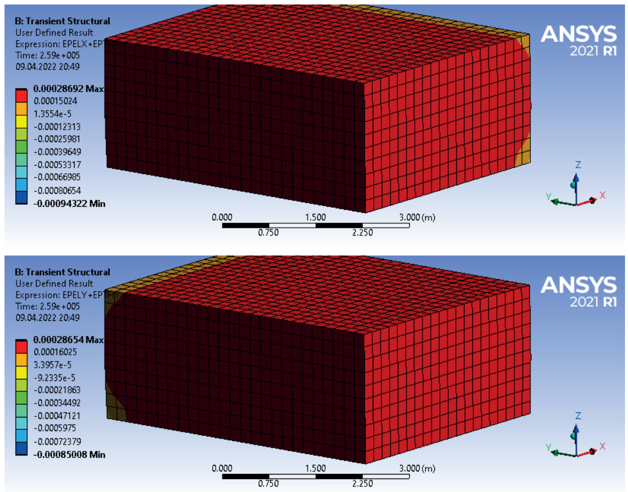

Figure 8. Total strain distribution for ε_x (top) and ε_y (bottom)

Based on these features, we propose the simplified method for calculating the stress-strain state.

In a biaxial stress state, the relationship between stresses and strains can be represented as:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) + \varepsilon_f;$$
$$\varepsilon_y = \frac{1}{E}(\sigma_y - \nu\sigma_x) + \varepsilon_f, \tag{11}$$

Here, the modulus of elasticity is taken as a function of coordinates, ε_f are the forced deformations, representing the sum of temperature deformations, contraction shrinkage deformations and creep strains:

$$\varepsilon_f = \alpha\Delta T + \varepsilon_{sh} + \varepsilon_{cr}. \tag{12}$$

At $\sigma_x = \sigma_y = \sigma$ and $\varepsilon_x = \varepsilon_y = \varepsilon$, expressing stresses from (11) in terms of strains, we obtain:

$$\sigma = \frac{E}{1-\nu}(\varepsilon - \varepsilon_f). \tag{13}$$

We assume that the soil under foundation slab does not prevent the free expansion of the foundation in the directions x and y. The ε value can be found from the condition that the axial forces $N = N_x = N_y = 0$:

$$N = \int_0^h \sigma dz = 0, \tag{14}$$

where h is the foundation slab thickness.
Substituting (13) into (14), we get:

$$\frac{1}{1-\nu}(\varepsilon\int_0^h E(z)dz - \int_0^h E(z)\varepsilon_f(z)dz) = 0, \tag{15}$$

From (15) it is possible to find ε:

$$\varepsilon = \frac{\int_0^h E(z)\varepsilon_f(z)dz}{\int_0^h E(z)dz}. \tag{16}$$

The proposed approach also makes it possible to take into account the reinforcement of the structure in the case when the coefficients of reinforcement along the x and y axes are the same.
The deformation of the i-th reinforcement layer can be written as:

$$\varepsilon_{s,i} = \frac{\sigma_{s,i}}{E_s} + \alpha_s\Delta T_{s,i}, \tag{17}$$

where α_s is the coefficient of linear thermal expansion of steel, E_s is the modulus of elasticity of steel.
We express from (17) the stress in the reinforcement and take into account that the reinforcement and concrete work together ($\varepsilon_{s,i} = \varepsilon$):

$$\sigma_{s,i} = E_s(\varepsilon - \alpha_s\Delta T_{s,i}). \tag{18}$$

The axial force represents the sum of the forces perceived by the reinforcement and concrete:

$$N = \int_0^h \sigma dz + \sum \sigma_{s,i}A_{s,i} = 0, \tag{19}$$

where $A_{s,i}$ is the cross-sectional area of the reinforcement of the i-th layer per 1 meter of the length of the slab.
Substituting (13) and (18) into (19), we obtain the following formula for ε:

$$\varepsilon = \frac{\int_0^h E(z)\varepsilon_f(z)dz + (1-\nu)\sum E_s\alpha_s\Delta T_{s,i}A_{s,i}}{\int_0^h E(z)dz + (1-\nu)\sum E_s A_{s,i}}. \tag{20}$$

CALCULATION ALGORITHM

The first step in calculating the stress-strain state of foundation slabs is to determine the temperature field. As mentioned earlier, with the exception of the edges of the foundation slab, the temperature distribution is one-dimensional, and to determine the function $T(z,t)$, instead of equation (1), one can use the equation:

$$\lambda(z,t)\frac{\partial^2 T}{\partial z^2}+Q=\rho c\frac{\partial T}{\partial t}. \quad (17)$$

To solve equation (17), a grid in z and t is introduced. When solving this equation by the finite element method, the problem is reduced to a system of differential equations

$$[C]\frac{\partial\{T\}}{\partial t}+[K]\{T\}+\{F\}=0, \quad (18)$$

where $[C]$ is the damping matrix, $[K]$ is the thermal conductivity matrix, $\{F\}$ is the load vector.

The integration of system (18) is carried out together with the solution of differential equation (5) using the Euler method or other difference schemes.

Further, at each time step, the stress-strain state is calculated.

Contraction shrinkage ε_{sh} is determined by the empirical formula [17]:

$$\varepsilon_{sh}(t)=-(0.2B-2)(a\ln t-b)\cdot 10^{-5}\le 0, \quad (17)$$

where B is the concrete class (MPa), a and b are the empirical coefficients

For quick hardening concrete $a=0.31$ and $b=0.4$, for slow hardening concrete $a=0.41$ and $b=0.85$.

To determine creep strains, a viscoelastic model of hereditary aging of concrete is used [13]. In the case of a biaxial stress state, the creep law is written as:

$$\begin{aligned}\varepsilon_x &= \frac{1}{E(t)}(\sigma_x(t)-\nu\sigma_y(t))- \\ &-\int_0^t(\sigma_x(\tau)-\nu\sigma_y(\tau))\cdot\frac{\partial C(t,\tau)}{\partial\tau}d\tau.\end{aligned} \quad (19)$$

The measure of creep was used in the form:

$$\begin{aligned}C(t,\tau)&=\frac{\varphi(\tau)}{E(t)}(1-e^{-\gamma(t-\tau)}),\\ \varphi(\tau)&=\frac{8000}{E(\tau)^{0.785}},\quad \gamma=0.05\,days^{-1}.\end{aligned} \quad (20)$$

From (18), the creep deformation, taking into account the equality of stresses σ_x and σ_y can be written as:

$$\varepsilon_{cr}=-(1-\nu)\int_0^t\sigma(\tau)\cdot\frac{\partial C(t,\tau)}{\partial\tau}d\tau. \quad (21)$$

The stress calculation is carried out step by step. The creep strains in the next step are determined from the strains and stresses in the previous step. If the forced deformation ε_f in each node is known at the current step, one can find the value ε using formula (20). And then the stress in each node can be calculated using formula (11).

RESULTS AND DISCUSSION

To test the developed technique, a test problem was solved for a foundation slab with dimensions $a = 8$ m, $b = 10$ m, H_f = 2 m. The initial temperature of the concrete mix, the ambient temperature, and the initial temperature of the soil were assumed to be the same and equal to 10.5 ^{0}C for simplicity. B25 class concrete was assumed with thermophysical properties: λ_∞ = 2.67 W/(m·^{0}C), ρ = 2500 kg/m^3, c = 1000 J/(kg·^{0}C). Thermal properties of the soil were: λ = 1.5 W/(m·^{0}C), ρ = 1600 kg/m^3, c = 1875 J/(kg·^{0}C). Heat transfer coefficients on the upper surface of the soil and on the top of the foundation were 25 W/(m^2·^{0}C) and 4.5 W/(m^2·^{0}C) respectively. The time interval from 0 to 72 hours was considered. Thermal expansion coefficient of concrete was α = 10^{-5} 1/^{0}C.

We have used for concrete the time dependence of the density of internal sources which is shown in Fig. 9.

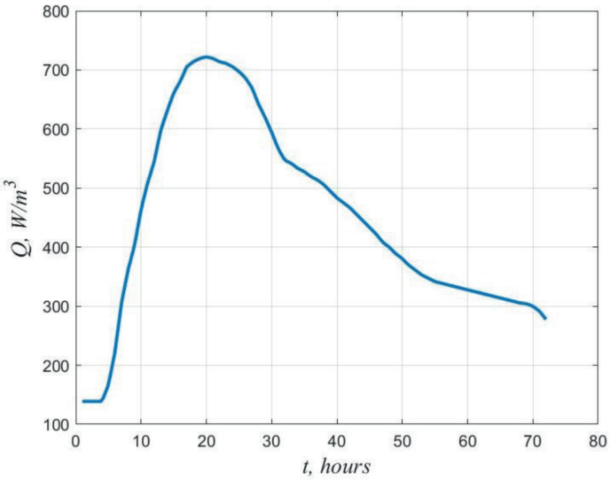

Figure 9. Dependence of the density of internal heat sources of concrete on time

The comparison was carried out with the solution in the ANSYS software package in a three-dimensional formulation. When calculating in ANSYS, the modulus of elasticity of concrete was assumed to be constant in time and equal to 2.45×10^4 MPa, which corresponded to the average value of the modulus of elasticity over the thickness of the slab at the age of 72 hours.

Figure 10 shows the change in time of the maximum temperature in the foundation and the temperature on the upper surface, obtained from the solution of a one-dimensional problem, taking into account the dependence of the thermal conductivity coefficient on the degree of hydration. The dashed lines correspond to the solution in the ANSYS software package in a three-dimensional setting at a constant thermal conductivity coefficient. From the graphs presented, it can be seen that, firstly, the conditions on the side surfaces of the foundation do not affect the temperature distribution in the center, and, secondly, the change in the thermal conductivity coefficient over time can be neglected.

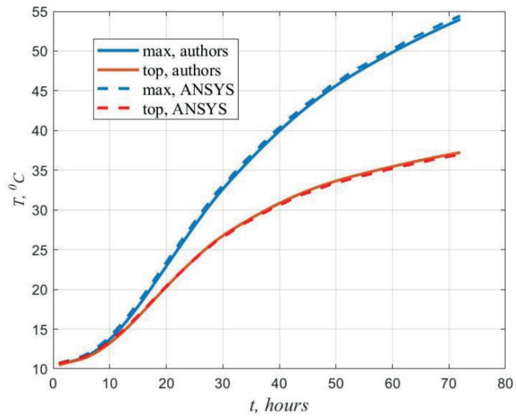

Figure 10. Time change of temperatures in the foundation

Fig. 11 and 12 show the change in time of stresses σ_x in the center of the foundation at the upper and lower surfaces respectively (at points with the highest tensile stresses). Curve 1 corresponds to the solution according to the author's method at a constant modulus of elasticity without taking into account creep and contraction shrinkage. Curve 2 corresponds to the solution taking into account the dependence of the elasticity modulus on the degree of concrete maturity, but without taking into account creep and contraction shrinkage. Curve 3 takes into account the dependence of the elastic modulus on time, creep, and contraction shrinkage. Curve 4 was plotted taking into account the factors listed above and a reinforcement factor of 2%. The dashed line shows the solution in the ANSYS software package.

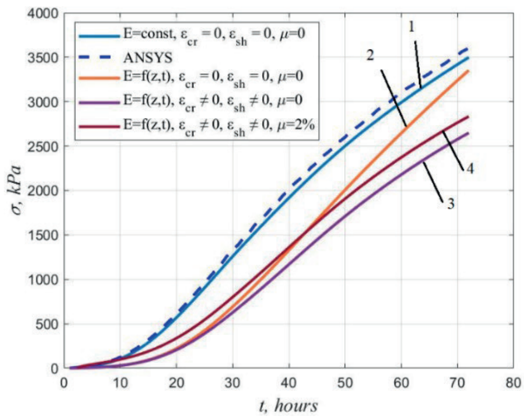

Figure 11. Change in stresses σ_x at the upper surface of the foundation

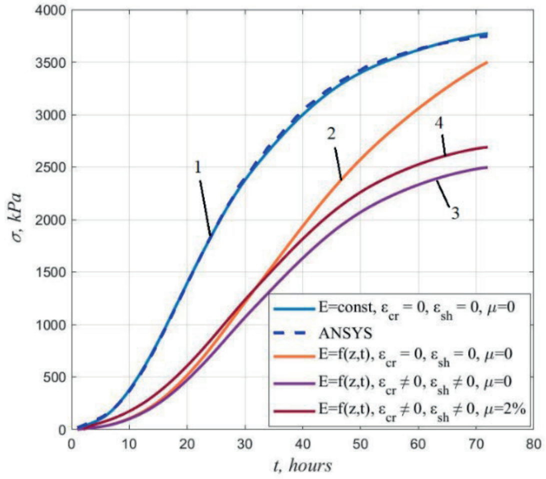

Figure 12. Stress σ_x change at the bottom surface of the foundation

Figures 11-12 show the following:

1. The results obtained with E = const according to the author's method and in the ANSYS software package differ slightly.
2. Neglecting the dependence of the elasticity modulus of concrete on the degree of its maturity leads to an overestimation of stresses in concrete.
3. Neglect of the concrete creep also leads to overestimation of stresses.
4. When reinforcement is taken into account, the stresses in concrete at the stage of construction are higher, which, firstly, can be explained by the presence of a small difference between the coefficients of linear thermal expansion of steel and concrete (α_s = 1.15·10^{-5} and α_b = 1·10^{-5}), and secondly by the contraction shrinkage of concrete.
5. With the accepted initial data, the tensile stresses in concrete during the curing process can reach almost 3 MPa. Similar results were obtained earlier in the works [14,18]. Obviously, concretes of mass classes (B25-B35) are not able to withstand such stresses, especially at the stage of structure formation, and measures are needed to reduce the risk of early cracking. Such measures include the regulation of the kinetics of heat release of concrete [19, 20] and the parameters of heat transfer on surfaces [21], the installation of cooling systems [22], etc.

CONCLUSIONS

A simplified, but at the same time effective method for determining the stress-strain state of massive monolithic foundation slabs during the construction process was proposed.

It was shown that the problem of calculating thermal stresses in massive monolithic foundation slabs can be reduced to a one-dimensional one without compromising the accuracy of the results.

The developed technique was tested by comparison with the results of calculations in the ANSYS software package in a three-dimensional formulation. The discrepancy between the results is insignificant.

The proposed method makes it possible to take into account the dependence of the modulus of elasticity of concrete on the degree of its maturity, creep, contraction shrinkage, and reinforcement coefficient.

It has been established that neglect of creep and changes in the modulus of elasticity of concrete over time leads to overestimated stress values. The contraction shrinkage of concrete and the difference in the coefficients of linear thermal expansion of concrete and reinforcement lead to the fact that with an increase in the coefficient of reinforcement, the stresses in concrete at the stage of construction increase.

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