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Long-term exploitation of reinforced concrete constructions of transport structures on a soil base under conditions of nonlinear rheological deformation with corrosion damage

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Abstract. The method of calculation of reinforced concrete constructions of transport structures on a soil base in an aggressive environment under rheological deformation conditions, taking into account corrosion damage, reflecting their real work under the combined action of load and aggressive environment on the basis of the modern phenomenological theory of deformation of elastic-creeping body, is proposed. The possibility of considering the processes of long-term deformation of reinforced concrete in conditions of long-term operation with a changing mode of action of external load is shown. An example of the calculation of a reinforced concrete flexible foundation on a soil base is given, taking into account the friction forces along its sole during the considered service life and the presence of corrosion damage.

1 Introduction

In conditions of long-term exploitation [1-4] of reinforced concrete constructions of transport structures in an aggressive environment under various loads, it is necessary to assess their stress-strain state as a result of corrosion damage, taking into account the reduction in the cross-sectional area of concrete and reinforcement.

During the operation of road coverings, airfield coverings, foundations of transport structures and other elements of transport infrastructure on a ground base made of concrete and reinforced concrete, a large number of various defects and damages arise due to both prolonged external loads and aggressive (non-violent) environmental influences.

Corrosion damage to reinforced concrete elements can affect the strength of the material, change the calculation schemes, redistribute strains in the cross-sections of the construction and break the joint work of concrete with reinforcement, as well as lead to other consequences that reduce the design life of the structures and other operational characteristics [5-9]. The most unfavorable result of the development of the corrosion process of reinforced concrete constructions is a decrease in their bearing capacity and suitability for normal operation,

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which leads to non-compliance with safety requirements and limit conditions under operating loads during the entire period of exploitation [10,11].

2 Materials and Methods

Based on the generally accepted practice, the stresses in the cross section of the reinforced concrete element before the formation of cracks is the sum of the forces perceived by the reinforcement and concrete [12,13], then it is obvious that the following formula can be obtained taking into account corrosion damage in concrete and reinforcement:

$$\sigma_x(t)A_x = \sigma_{b,x}(t)K_b(z,t)A_{b,x} + \sigma_{s,x}(t)\omega_s(t)A_{s,x} \quad (1)$$

where: $\sigma_x(t)$ - the average stress in the section of the reinforced concrete element; $\sigma_{s,x}(t)$ and $\sigma_{b,x}$ (t) – are the averaged stresses in reinforcement and concrete; $A_{b,x}$ and $A_{s,x}$ – correspond to the values of the area of reinforcement and concrete; $K_b(z,t)$ – is a coefficient that takes into account the degree of corrosion damage to concrete, changing over time of observation; $\omega_{s,x}$ (t) - is a similar coefficient for taking into account corrosion damage to reinforcement.

The coefficient that takes into account the degree of corrosion damage to concrete is defined as:

$$K_b(z,t) = \left\{1 - \left[\frac{P}{\beta(t,t_0)}\right]\right\} = \frac{2P}{\beta^2(t,t_0)}z - \frac{1}{\beta^2(t,t_0)}z^2 \quad (2)$$

where- $\beta(t,t_0)$ - the value of the damage [5]; z – the vertical coordinate within the height of the cross-section; $x=\delta(t,t_0)+p$ – the height of the compressed concrete zone; p - the undamaged part of the cross-section (fig. 1.).

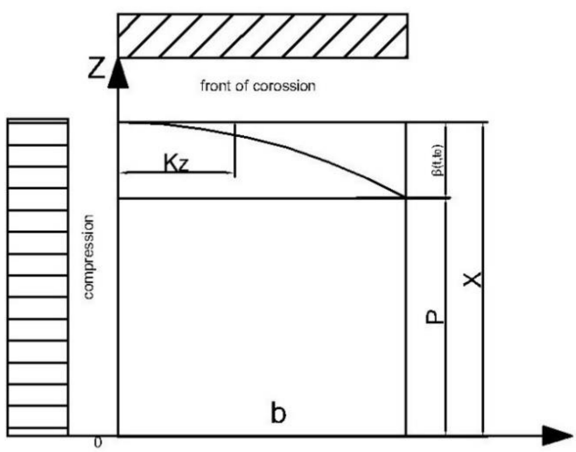

Fig. 1. One-sided corrosion damage of the concrete simplest sample.

For reinforcement that have been subjected to corrosion damage, its area must be considered taking into account the decrease over time:

$$A_s = \omega_s(t)A_{so} \quad (3)$$

A_{so} – is the area of the intact reinforcement, $\omega_s(t)$ – is a coefficient that takes into account the decrease in the area of the reinforcement as a result of corrosion, determined by the formula:

$$\omega_s(t) = \left[1 - \frac{2\theta(t,t_0)}{D} + \frac{16\theta^2(t,t_0)}{\pi D^2}\right] \tag{4}$$

where: D is the diameter of the reinforcement;

$$\theta(t, t_0) = \frac{k}{\sqrt{a}} t^n \tag{5}$$

In case of a crack, you can use the well-known assumption of V.I. Murashev [13]:

$$\sigma_s = \psi_{s,m}\, \mu_s\, \omega_s\, (t, t_0)\sigma_{s,m}\, (t, t_0); \quad \varepsilon_s = \frac{\sigma_s}{E_s} = \frac{\psi_{s,m}\, \mu_s\, \omega_s\, (t,t_0)\sigma_{s,m}\, (t,t_0)}{E_s^0} \tag{6}$$

in which: σ_s – is the average stress occurring in the reinforcement in the area between the cracks; $\psi_{s,m}$ – is a coefficient that takes into account the effect of coupling of reinforcement and stretched concrete; μ_s– is the reinforcement coefficient in this direction; $\sigma_{s,m}$– is the stress in the reinforcement in the area with cracks appearing; $\varepsilon_{s,}$– is the relative average deformations in the reinforcement sections between the cracks appearing; $E^0{}_s$ – is the elastic modulus of the reinforcement.

The current state of methods for calculating reinforced concrete constructions due to force and non-violent influences does not fully correspond to the actual work of materials. This is explained by the fact that the above conditions of deformation of reinforced concrete are taken into account only indirectly by modern regulatory documents [14].

In conditions of long-term exploitation of reinforced concrete constructions, it is necessary to assess their stress-strain state as a result of corrosion damage, determine reliability, durability and residual service life, taking into account the reduction in the cross-sectional area of concrete and reinforcement.

Modern calculation methods should be based on taking into account the real properties of materials under the influence of external loads, taking into account their degradation in long-term exploitation. As evidenced by the majority of experimental data, the foundation soils and foundation structures made of reinforced concrete have pronounced nonlinear and rheological properties, i.e. the process of their deformation proceeds non-linearly and depends on the nature and duration of the external load, and long-term operating conditions of structures in the soils of the bases should assume consideration of corrosion processes. In real conditions, foundation structures react not only to the magnitude of the applied load, but also to the specifics of its changes over time, as well as corrosion damage.

Consideration of rheological properties, loading conditions and corrosion damage is an important factor in the calculation of constructions and foundations due to the fact that they are under the influence of cyclically varying loads and corrosion processes during operation [5].

The proposed article attempts to bring the calculation method as close as possible to the actual operation of materials under the influence of time-varying external load and corrosion damage. Consider a flexible foundation loaded in the middle with a concentrated force that changes cyclically over time, and we will assume that the rate of its change over time is small and the resulting inertia forces can be neglected due to their smallness, i.e. we will calculate according to a static scheme. We will search for the solution of the problem using the discrete method. We write down the resolving equations of the mixed method, taking into account the horizontal friction forces arising in the contact zone of the beam with the base for the elastic linear formulation of the problem in the same way [6]:

$$\{\delta\}\ \{W\} + \{\Delta_p\} + \{Y\} = 0$$

$$\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} X_i = 0 \tag{7}$$

$$\sum_{i=1}^{n} S_i - \sum_{i=1}^{n} T_i = 0$$

$$\sum_{i=1}^{n} M_0(P_i) + \sum_{i=1}^{n} S_i y_i - \sum_{i=1}^{n} X_i a_i - \frac{h}{2}\sum_{i=1}^{n} T_i = 0,$$

$\{\delta\}$ - single displacements in the main system (Fig.2); $\{W\} = \begin{Bmatrix} X_i \\ T_i \end{Bmatrix}$ - searching unknowns; X_i - unknown vertical reaction; T_i - unknown horizontal reaction; $\{\Delta p\}$ - cargo displacements in the main system; $\{Y\} = \begin{Bmatrix} u \\ v \\ \varphi \end{Bmatrix}$ - beam sealing displacements in the main system; u - horizontal displacement; v - vertical displacement; φ - angle of rotation; P_i- external vertical load; S_i- external horizontal load.

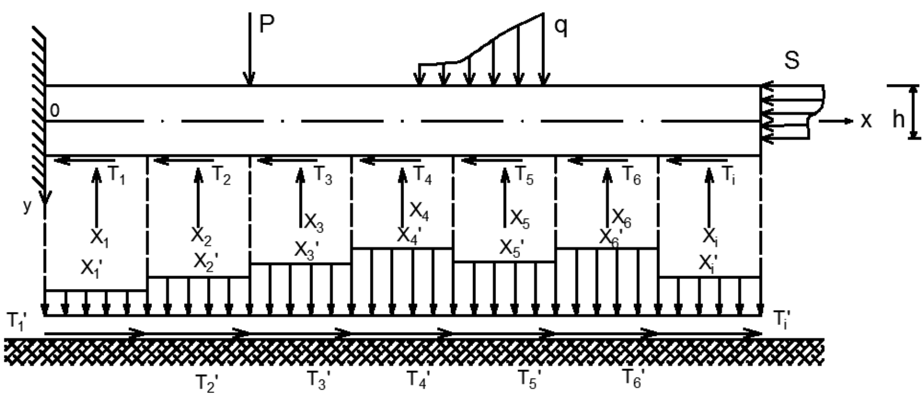

Fig. 2. The main system.

Single displacements in the main system in the direction of the desired unknowns consist of three components: vertical displacements of the base from a single load; horizontal displacements of the base from a horizontal single load and bending of the beam from the action of single vertical and horizontal forces determined by the usual More-Vereshchagin rule:

$$\delta = \frac{1-\nu_0^2}{\pi E^e(v,t)} \iint_0^F \frac{X(\xi)d\xi\, d\eta}{\sqrt{(X-\xi)^2 + (y-\eta)^2}} + \frac{(1-\nu_0)(1-2\nu)}{2\pi E^e(v,t)} \cdot \iint_0^F \frac{T(\xi)(X-\xi)d\xi d\eta}{(X-\xi)^2 + (y-\eta)^2} + \int_0^l \frac{M_i M_k}{D}\, dv \tag{8}$$

Making the transition to a nonlinear and nonequilibrium problem, we use Harutyunyan's theorem on the identity of the stress-strain state in an elastic and elastically creeping array, extended to the case of nonlinear deformation, we obtain an expression for displacements [1]:

$$\delta = \frac{1-\nu^2}{\pi E^e(v,t)} S_m \left[\frac{P(t)}{R}\right] \iint_0^F \frac{P(\xi)d\xi d\eta}{\sqrt{(X-\xi)^2+(y-\eta)^2}} - \frac{1-\nu^2}{\pi} \int_{t_0}^{t} \iint_0^F \frac{P(\xi,\tau)d\xi d\eta}{\sqrt{(X-\xi)^2+(y-\eta)^2}} \cdot xS_n \left[\frac{P(\tau)}{R}\right] \frac{\partial C(t,\tau)}{\partial\tau} d\tau + \frac{(1+\nu)(1-2\nu)}{2\pi E^e(v,t)} S_n \left[\frac{T(t)}{R}\right] \iint_0^F \frac{T(\xi)(X-\xi)d\xi d\eta}{\sqrt{(X-\xi)^2+(y-\eta)^2}} - \frac{(1+\nu)(1-2\nu)}{2\pi} \int_{t_0}^{t} \iint_0^F \frac{T(\xi,\tau)(X-\xi)d\xi d\eta}{\sqrt{(X-\xi)^2+(y-\eta)^2}} S_n' \left[\frac{T(t)}{R}\right] \frac{\partial C(t,\tau)}{\partial\tau} d\tau + \int_{t_0}^{t} \int_0^{l} \frac{M_i M_k}{D(\tau)} dv d\tau \tag{9}$$

where: S_m and S_n are the deformation nonlinearity functions used in the form:

$$S = \left[1 + \eta \left(\frac{P}{R}\right)^m\right] \tag{10}$$

E(t) and c(t,τ) are, respectively, the modulus of elastic instantaneous deformations and the creep measure; D(τ) is the rigidity of the reinforced concrete section, taken in the form proposed in [2]:

$$D(t) = E^e(v,t) \left[\frac{K_b(t)bX^3}{12} + bx\left(q_0 - \frac{X}{2}\right)^2\right] + E_a'\omega_s(t)A_a'(q_0 - a')^2 + \frac{E_a\omega_s(t)A_a}{\psi_a}(h_0 - q_0)^2 \tag{11}$$

$$\frac{1}{E^0(v,t)} = \frac{1}{E^0(t)}\left[1 + \eta_m \langle\frac{P(t)}{R}\rangle^m\right] + C(t,t_0)\left[1 + \eta_n \langle\frac{P(t)}{R}\rangle^m\right] \tag{12}$$

where: E^e(v,t) is an integral modulus of deformations, taking into account the nonlinearity of deformation; $E_0(t)$ is an elastically instantaneous modulus of deformations; C(t,t_0) is a measure of creep.

Similarly, [4] we take the law of variation of the coefficient of transverse deformations in the form:

$$\nu = \frac{1}{2}\left[1 - (1 - 2\nu_0)\frac{E^e(v,t)}{E_0(t)}\right], \tag{13}$$

where ν_0 is the Poisson's ratio.

The change in the external load characteristic of the building during exploitation will be accepted according to the law shown in Fig.3.

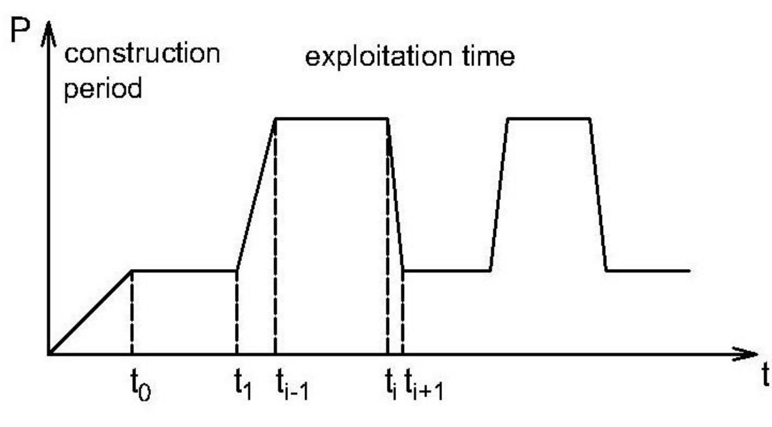

Fig. 3. Graph of external load changes.

$$P(t) = \begin{cases} \alpha_i t P_i; & t_i \leqslant t \leqslant t_{i+1} \\ P; & t_{i-1} < t < t_i \end{cases} \tag{14}$$

Note that the graph shown in Fig.3 is somewhat idealized, however, the actual change in the external load can be clarified using probabilistic methods used in modern structural mechanics.

The joint consideration of equations (1-4) and (7-12) turns a linear problem of the mixed method into a nonlinear one, the solution of which in a closed form meets insurmountable mathematical difficulties. Therefore, to obtain an engineering-observable solution in numerical form, the method of integral estimates is used [2], which allows you to linearize the problem.

The essence of this technique is as follows. The entire loading process is sampled in time for certain (rather small) intervals determined by the required calculation accuracy, for which the corrosion and creep processes are fixed. In each time interval, the solution of a nonlinear problem for a constant load is carried out using a linear apparatus of structural mechanics based on the method of successive approximations. The design is divided into a certain number of sections, also determined by the required calculation accuracy, and in the first approximation, the problem is solved in an elastic-linear formulation. In the second approximation, according to the obtained values of bending moments for each section, the rigidity of the reinforced concrete section is specified according to the (11), and according to the plot of the ground vertical stresses and the plot of tangential stresses, the values of the functions S_m, S_n , v and $E^e(v,t)$ for the soil base are assigned, i.e. the values of single displacements are specified according to formula (8) and the problem is solved again. Then a third approximation is carried out, and so on, until the difference between two adjacent values of δ reaches a predetermined degree of accuracy. In the event of a divergent iterative process, well-known mathematical methods are used to improve convergence. Then they move on to the next fixed time interval, for which the external load will change by a certain amount, and the above-mentioned computational process is repeated again and so on, until the entire time interval under consideration is exhausted.

3 Results

As an illustration of the above calculation method, an example of a flexible ribbon foundation of a residential building is shown in Fig.4. The foundation soil has the following physical and mechanical characteristics: $E_0(t)$ = 20 MPa, R = 0.25 MPa, η_m = 1,29; m = 2,48; ν = 0,3; η_n = 2,3; $c(t,t_0)$ = 0,00278 $\frac{1}{\text{MPa}}$; γ = 0,025 1/hour. The beam material is concrete B30, beam width b =40 cm, height h = 60 cm reinforcement class A-400, the values of the parameters of the nonlinearity of concrete, creep, corrosion characteristics and other necessary data are given in [2]. The parameters of the change in the external load α = 0.0007, t = 60 days, P = 750 KN and corrosion damage to the reinforcement k= 1.62, n = 0.68, the thickness of the protective layer of concrete a = 30 mm. The nonlinearity of the friction forces in the contact zone of the beam and the base, as well as the variability of the coefficient of transverse deformations were not taken into account. The calculation with some simplifications was carried out only for the period of 50 years of exploitation of the building (see Fig.4).

Analyzing the calculation results, the following conclusions can be drawn: with an elastically linear formulation of the problem, taking into account the friction forces arising along the sole of the flexible foundation leads to a decrease in the maximum bending moment up to 15%.

Taking into account the friction forces arising along the sole of a flexible foundation, non-linearity, rheology of deformation and corrosion damage with a regime change of external load leads to the transformation of soil plots and bending moments in the direction of leveling forces, which is explained by the phenomenon of redistribution of forces from more loaded sections and components of sections to less loaded ones, characteristic of the soils of the foundation and reinforced concrete constructions.

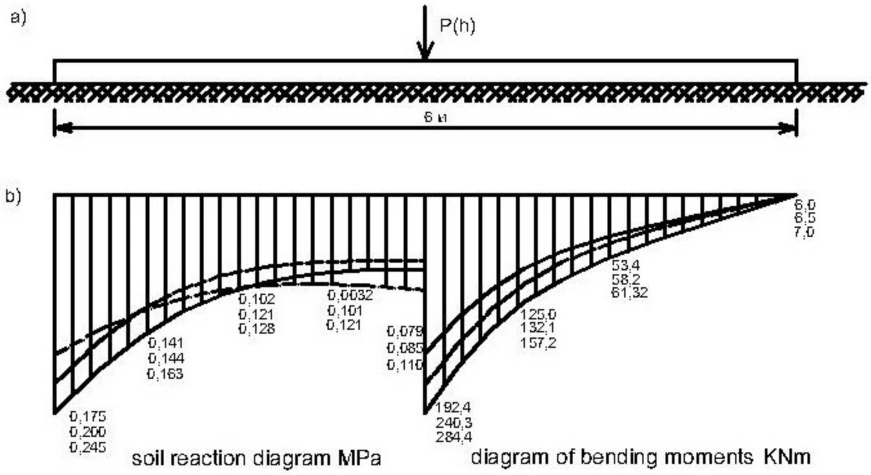

Fig. 4. Design scheme and applied forces.

Where: — — — – elastic-linear formulation with the friction forces;

——— - elastic-linear formulation;
—. —· —· – non-linear and rheological formulation taking into account the mode of action of external load and corrosion damage with an operational period of 50 years.

With a nonlinear and non-equilibrium formulation of the problem, with consideration the mode of action of the external load and corrosion damage, the decrease in the maximum ordinate of the ground repulse plot was 27%, and the increase in the minimum was 14%. The reduction of the maximum bending moment was 22%.

4 Conclusions

The proposed methodology makes it possible, even at the design stage, to assign the characteristics of constructions elements of transport structures, taking into account the duration of service life, nonlinearity and rheology of deformation, as well as the possibility of consideration corrosion damage, which will allow determining the dimensions of cross-sections and assigning the required classes of concrete and reinforcement, taking into account the listed factors.

A more complete account of the real properties of the soils of the foundations and reinforced concrete constructions of the foundations, taking into account the mode of action of external loads and corrosion damage, allows not only to clarify the stress-strain state, but also to ascertain the nature of its changes during loading and unloading, which will help to find additional strength reserves and ensure material savings during long-term operation of transport infrastructure structures.

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