Nonlinear deformation of concrete structure elements taking into account compensation grouting and fracturing

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Abstract. A formulation of the problem of compensatory injection was implemented using consistent equations of the elastic geometrically nonlinear three-dimensional theory. Algorithm for numerical solution was developed within the framework of the finite element method. A technique had been developed for the processes of crack formation in elements with prestressed reinforced polymer composite. A model problem was solved and comparison with experimental data was made.

1 Introduction

The intensity of underground construction in the urban area requires builders to ensure the safety of civil facilities and structures that fall within the construction zone [1]. Basically, to protect construction objects in the zone of their bases and foundations, additional soil reinforcement is applied [2-3]. One of the options for limiting the development of additional deformations of the bases of foundations of buildings and structures is the technology of compensatory injection. The use of this approach [4-5] makes it possible to compensate practically any additional foundation base settlement by injecting concrete mortar under high pressure into the area of the foundation base of a building or structure.

Recently, interest in the use of polymer-composite reinforcement has increased significantly due to its corrosion resistance, low specific density and high axial tensile strength [6-7]. However, it should be taken into account that the modulus of elasticity of polymer-composite reinforcement is much closer to concrete than to steel. A number of works note that the load-bearing capacity of the structure is primarily affected by the weak adhesion between concrete and polymer composite reinforcement [8-10]. However, the problem of high deformability of polymer composite reinforcement as a heterogeneous and structurally complex material remains.

One of the possible ways to solve the problem of high deformability of concrete structures and, at the same time, high cracking is the use of prestressed polymer composite reinforcement [11].

The study of deformation processes of modern building structures is in most cases connected with numerical methods. It is very convenient to base these methods in the

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framework of nonlinear finite element analysis: monographs [12-13] and papers [14-22] are examples. In this work, the defining relations linking the increments of "true" (according to V.V. Novozhilov) stresses and increments of "true" strains are used. The methodology proposed by the authors was partially presented in [23-24].

2 Problem statement

2.1 Algorithm for determining soil settlement in the zone of compensatory injection

The essence of the compensatory injection method is the injection of a slowly hardening mineral-based mortar with the required viscosity into previously prepared soils of the base of a building or structure to prevent further settlement or to compensate for it. This allows, in particular, forming the calculated stress-strain state of the soil massif, which provides a controlled lifting of the above-ground structure, using the effect of a jack placed under its entire area at the base.

Within the framework of numerical analysis, such an approach can be easily implemented by imparting additional properties to the volume occupied by the pipe for injection of concrete solution.

Firstly, it can be assumed that this injected mortar has its own (compared to hardened concrete) mechanical characteristics. The change in these characteristics can be carried out discretely, since the proposed calculation method is based on the use of consistent equations of the nonlinear theory of elasticity [25].

Secondly, in order not to introduce mass balance equations into the general system of resolving equations, consider the injected concrete as a thermoelastic material with a reduced (fictitious) coefficient of thermal expansion, and for the rest of the soils in which the solution is injected, this coefficient is considered zero [25]:

$$\sigma_y = \lambda e y e_y + 2 \mu e_y - 3 K \alpha T \delta_y,$$

where $\sigma_y, e_y$ are the components of the stress and strain tensors, $\lambda, \mu$ are the elastic constants of the material, $K$ is the bulk modulus of elasticity, $\alpha$ is the linear coefficient of thermal expansion, $T$ is the change in temperature.

Further, with an increase in the "fictitious temperature" of the solution, it will expand and burst the surrounding soils. At each step of injection ("increase in temperature") discretely increase the density of the solution.

Thirdly, at the boundary of the solution and bursting soils, introduce the contact condition [23-24].

This technique is quite simple and effective for assessing the change in soil settlement in the zone of compensatory injection.

2.2 Algorithm for taking into account the processes of crack formation in concrete

The algorithm for taking into account the processes of crack formation in concrete soil is similar to the method for determining plastic deformation zones in continuous media, only the relationship between increments of true stresses and strains is carried out according to the formula
When implementing the algorithm within the framework of the finite element technique, the plasticity condition, or, as in this case, the condition for the occurrence of a microcrack, is checked at each Gaussian quadrature integration point. If this condition is reached at a certain loading step, then the area along which the crack has started is determined. The impossibility of resistance to separation at a given point is carried out by integrating the stiffness matrix in the axes associated with the normal directions to the separation area. In the same axes, one can take into account the presence or absence of friction at the edges of this microcrack. At the same time, at each load step within the iterative process, the stress-strain state in the beam will be redistributed, and the beam will retain its bearing capacity due to reinforcement for some time.

3 Numerical results

3.1 Simulation of cracking processes in a concrete beam with prestressed polymer composite reinforcement

A three-dimensional concrete beam reinforced with two polymer composite rods is calculated. Experimental data for this problem were presented in [23]. Figure 1 shows the scheme of support and loading of the calculated three-dimensional beam. Concrete beam (B25), 0.12 x 0.2 x 1.8 m in size, reinforced with glass rods. The lower reinforcement is prestressed – Ø6 SPA, the upper zone - reinforcement – Ø4 SPA.

Fig. 1. Scheme of support and loading of the calculated beam.
In Figure 2 is shown the dependence of the load $P$ on the deflection $f$, where curve 1 obtained according to the experimental results from [23] and curve 2 obtained according to the proposed method.

![Figure 2](image)

**Fig. 2.** The dependence of the load $P$ on the deflection $f$, 1 – according to the experimental results from [23]; 2 – according to the proposed method.

Figures 3 and 4 show a comparison of the solution the problem obtained in ANSYS and ABAQUS respectively, taking into account cracking using the XFEM method.

![Figure 3](image)

**Fig. 3.** Comparison experiment and simulation (ANSYS) results.
Fig. 4. Comparison experiment and simulation (ABAQUS) results.

Fig. 5. Simulation results of cracks development during loading (ABAQYS).

Fig. 6. Simulation results of cracks development during loading (ANSYS).

4 Conclusion

It can be noted that the method proposed in the paper for taking into account the effect of compensatory injection on the deformation of closely spaced underground structures and soils is quite effective in determining settlement. The determination of the stress-strain state in the immediate vicinity of the injected solution leaves much to be desired.

The calculation method proposed in the paper makes it possible to simulate, with sufficient accuracy, the processes of crack formation in concrete beams with prestressed polymer composite reinforcement.

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