The results of determining the structural elements’ displacements when using various soil models and software systems

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Abstract. Taking into account the nonlinearity of the structures base soil work of the of the during geotechnical calculation makes it possible to adequately determine the stress-strain state (SSS) of structural elements and, in general, the base - foundation - structure system.

Introduction

When solving the problems associated with the structures’ stress-strain state (SSS) determination, it is necessary to take into account the structures’ work in the base - foundation - structure system [1, 2, 3, 4]. The most significant contribution to the change in SSS at constant loads can be made by the rigidity of the foundation.

Currently, the calculations of the stress-strain state (SSS) of the hydraulic structures’ foundations are mainly carried out using the software systems that implement the finite element method (FEM), this is due to the presence of a complex configuration of structures both in the elevated part of the structure and in the land portion, complex engineering geological conditions, etc.

The base stiffness parameters determination is carried out by calculating coefficient of subgrade resistance \( C_1 \), \( C_2 \) [5, 6].

The most common models for calculating the coefficient of subgrade resistance \( C_1 \) (kN/m\(^3\)) and the shear coefficient \( C_2 \) (kN/m) are: the Winkler-Fuss model and the Pasternak model. In these models, when determining the coefficients, the nonlinear work of soils is not taken into account, which means that the change in the base shape under the structure is not accurately determined.

Such soil models that take into account the non-linear operation of soils - this is the Mohr-Coulomb model and the elastic-plastic model with soil hardening (Hardening Soil) exist.

Material and technology

In order to analyze the effect of nonlinear soil work on the SSS of the elevated water structures located in difficult engineering and geological conditions, the simulation was performed in the Stark ES software package [7, 8, 9]. As a result of the simulation, the maximum vertical displacements were numerically equal to –0.055 mm, the vertical displacements in one of the sections were –0.032 mm.
The results of the membrane stresses calculation in the pressure face of the water structure with the stiffness parameters of the base, calculated according to the Winkler-Fuss model, are presented in the following Figures 1 - 6.

The calculation results, visualized types of the water structures and the characteristics of the membrane stress values in the “r” direction are presented in Figure 1.

**Figure 1.** Visualized view of the water structure and design characteristic values

The estimated characteristic values: \( \text{Min } S_r = -88.8745 \text{ kN/m}^2 \); \( \text{Max } S_r = 606.561 \text{ kN/m}^2 \)

The calculation results, visualized types of water structures and the characteristics of the membrane values in the “s” direction stress are presented in Figure 2.

**Figure 2.** Visualized view of the water structure and the calculated characteristics values

The estimated characteristic values: \( \text{Min } S_s = -193.452 \text{ kN/m}^2 \); \( \text{Max } S_s = 189.499 \text{ kN/m}^2 \)

The calculation results, visualized views of the water structure and the characteristics of \( M_r \) bending moments are shown in Figure 3.
The estimated characteristic values: Min Mr = -78.0656 kNm/m; Max Mr = 99.7986 kNm/m

Figure 3. Visualized view of the water structure and the design characteristic values

The calculation results, visualized types of water structures and characteristics of the values of bending moments Ms are presented in Figure 4.

The estimated characteristic values: Min Ms = -45.7494 kNm/m; Max Ms = 163.47 kNm/m

Figure 4. Visualized view of the water structure and the design characteristic values

The calculation results, visualized types of the water structure and the shear forces characteristics at the site perpendicular to the r axis are presented in Figure 5.

The estimated characteristic values: Min Qr = -282.951 kN/m, Max Qr = 250.375 kN/m
**Figure 5.** Visualized view of the water structure and design characteristic values

The calculation results, visualized types of the water structure and the shear forces characteristics at the site perpendicular to the s axis are presented in Figure 6.

The estimated characteristic values: Min $Q_s = -250.984$ kN/m, Max $Q_s = 104.626$ kN/m

**Figure 6.** Visualized view of the water structure and the design characteristic values

The total displacement calculation results $U_{tot}$ are presented in Figure 7, calculated on the basis of the condition $U_{tot} = \sqrt{Ux^2 + Uy^2 + Uz^2}$.

Max moving = 0.973806 mm in knot 3284

**Figure 7.** The full movement isofields

Next, the vertical displacements analysis in the calculated sections was performed using a specialized geotechnical software complex for modeling the interactions between the structures and their foundations based on the finite element method GTS NX [10, 11, 12, 13, 14].

The calculation model for one of the sections in which the vertical displacements obtained as a result of modeling in the Stark ES software package amounted to $\sim 0.032$ mm is shown in Figure 8.
Figure 8. Calculation model

The following materials were used in the calculation model:
– Isotropic, which is used to model the behavior of most linearly elastic, nonlinear elastic and elastoplastic materials;
– Interface / Pile, which is used to model the behavior of the interaction (contact) between the base and the structure (contact / pile).

The following elements were used for the mathematical description of the structures’ operation with soil base:
– 1D element –is a one-dimensional element, which is an element having 2 or 3 nodes and a geometric length property;
– 2D element –is a two-dimensional element representing elements of a triangular and quadrangular shape having a geometric area property.

The relation between stresses and strains of isotropic materials for the two-dimensional calculation case \( \tau_{yz} = \tau_{zx} = y_{yx} = y_{zx} = 0 \), and in particular for the calculation according to the planar deformation scheme \( \varepsilon_{xx} = 0 \), using the strain modulus values \( E \), the Poisson’s ratio \( \nu \) and the thermal expansion coefficient \( \alpha \) set out in [3].

In the presented numerical simulation of the situation at the object, the Mohr-Coulomb model is selected for the strength criterion, which is most often used to model the soil bases’ behavior, since it demonstrates fairly reliable results in general non-linear soil calculations.

Mohr-Coulomb (Mohr-Coulomb model) is a simple and well-known linear elastoplastic model. The linear elastic part of the Mohr-Coulomb model is based on Hooke’s law of isotropic elasticity. The plastic part is based on the Mohr-Coulomb fracture criterion formulated as a part of unbound plasticity. Plasticity involves the irreversible deformations’ development. The basic principle of elastic-plasticity is that the deformations and strain rates are decomposed into the elastic part and the plastic part, which is expressed by the following relationships:

\[
\varepsilon = \varepsilon^e + \varepsilon^p \\
\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^p.
\]  

(1)

Hooke’s law is used to relate the stress velocities to elastic strain rates. Substitution of the above-mentioned equations according to the Hooke’s law leads to the following transformation:

\[
\dot{\sigma}' = D^e \dot{\varepsilon}^e = D^e \left( \dot{\varepsilon} - \varepsilon^p \right).
\]

(2)
According to the classical theory of plasticity, the plastic deformation rates are proportional to the derivative of the yield stress function with respect to stresses. This means that the plastic strain rates can be represented as the vectors perpendicular to the yield surface. This classical theory form is called “associated plasticity”.

The analysis of vertical movements in the calculated sections was carried out at the stage of the developed excavation pit (stage 4) and the erected structure (stage 6).

The results of the vertical displacements’ calculation at 4 stages, in the studied design section are presented in Figure 9.

![Figure 9. Vertical movements in 4 stages](image)

Analyzing the obtained results, we note that the maximum vertical displacements are numerically equal to 12.1 mm, while the soil pressure is observed.

The results of the vertical movements calculation at stage 6 are presented in Figure 10.

Analyzing the obtained results, we state that the maximum vertical displacements are numerically equal to –13.79 mm.

It should be noted that the vertical displacements defined by the Stark ES PC with the base stiffness determined by the Winkler-Fuss model are –0.032 mm.

![Figure 10. Vertical movements at stage 6](image)
Similarly, the vertical displacements were determined for other design sections.

**Summary**

The presented data make it possible to state that, with an incorrectly selected either the structure soil base design model or the design software package, a significant underestimation of the vertical displacements calculated in the Stark ES PC occurs when using the coefficient of subgrade resistance for modeling the base stiffness, determined by the Winkler-Fuss model.

When choosing any calculation model of the structure soil base, or the calculation software package, it is necessary first of all to focus on the analysis and prevention of the soil blockage formation violating its integral structure and leading to the loss of bearing capacity and stability.

The calculation results’ analysis showed that the base stiffness parameters and, as a consequence, the vertical displacements significantly affect the SSS of the elevated structures.

Based on the results of numerical modeling of the object’s state, we can unequivocally state that more realistic results are obtained using the software package GTS NX.

As a result of the topic study and the analysis of various approaches to calculating the hydraulic structures’ foundation deformations, it has been established that, for the mass construction structures, such soil models as Elastic and Mohr-Coulomb model are the most widely used.

However, the following disadvantages are inherent in these models, they do not take into account: non-linearity of deformation during loading; the soil’s hardening and softening; do not take into account the dependence of the soil’s mechanical properties on the speed of their loading, etc.

Scientific and technological progress and a modern approach to ensuring the mechanical safety of hydraulic structures leads to the need to use more “advanced” models - the model of hardened soil (Modified Mohr-Coulomb model) to describe the soil properties of the hydraulic structures’ foundation. Neglecting the phenomena characteristic of soils does not allow to obtain the necessary reliability of the results.

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