The influence analysis of the structures and applied software systems’ soil foundations design models

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Abstract. In difficult engineering and geological conditions, the water-supporting elevated structure’s design is carried out taking into account the base soil model, as well as the correctly selected software package, which allows to determine the stress-strain state (SSS) of the structure and as a result, all structural and technological parameters qualitatively.

Introduction

Ensuring the hydraulic structures’ safety is an important task. At the same time, the structures’ long service life, complex engineering and geological conditions, as well as the seismicity of the construction site introduce certain limitations. In fact, it is easier to foresee the situation in advance to prevent the destruction of the structure as a whole. Identification of hazardous areas, monitoring them, timely overhauls allow avoiding the loss of the facility’s performance, and ensure the structure’s safety. Preventive repairs are also more cost-effective than restoring the damaged structures and eliminating the accidents’ consequences that are significant from the hydraulic structures’ destruction. The use of modern programs based on numerical modeling makes it possible to predict the work of not a separate structure, but of the base – foundation – elevated structure. This approach allows to assess the failure impact of any element on the system as a whole and to ensure the water support structure’s optimal, safe operation.

As it was established earlier [1, 2, 3, 4, 5], the base rigidity makes a significant contribution to the stress-strain state (SSS) of structures, especially if the loads do not change. When solving the problems of determining the SSS in the elevated water-bearing structures, it is mandatory to take into account all the structural elements: base – foundation – structure system [6, 7, 8, 9].

Material and technology

Determining the stiffness parameters of the base is often done by calculating the subgrade resistance coefficients $C_1$, $C_2$ [10, 11, 12].

The most common models for calculating the coefficients for subgrade resistance $C_1$ (kH/m³) and the displacement factor $C_2$ (kH/m) are:
– the Winkler-Fuss model:
\[ C_1 = \frac{\sigma_0}{u}; \quad C_2 = 0; \]

– the Pasternak foundation model:
\[ C_1 = \frac{E_p}{(1-2v_{ap})H_c}; \quad C_2 = \frac{E_{eq}H_c}{6(1+v_{ap})}; \]

In this case, the sediment and the depth of the compressible stratum is calculated in accordance with the normative documents. For the finite element method, a calculation at each calculation point, with coordinates (x, y) at the depth \( z_i \), from each k-th external load on the ground is implemented, the calculation of additional vertical stress has the form:

\[ \sigma zp_{ik} \]

The calculation of the total additional vertical stress from the loads has the form:
\[ \sigma zp_i = \sum \sigma zp_{ik} \]

The depth calculation \( z_i \) vertical stress from the dead weight of the soil has the form:
\[ \sigma zg_i \]

Starting from the depth \( z_i \) and lower if the condition is satisfied:
\[ \sigma zp_i < k \cdot \sigma zg_i \]

The fixed depth of compressible thickness is:
\[ H_c = z_i \]

The coefficient \( k \) is used to determine the depth of compressible thickness \( H_c \).

Base draft \( S \) at the calculated point is determined by the formula, by the method of layer-by-layer summation:
\[ S = \beta \sum_{l=1}^{n} \frac{(\delta_{z,p,l} - \delta_{z,y,i}) \cdot h_i}{E_i} + \beta \sum_{l=1}^{n} \frac{\delta_{z,y,l} \cdot h_i}{E_{el}} \]

Under natural conditions, such a complex, three-phase substance as soil at the base of structures cannot be functionally connected by the linear relationships. At the same time, the presented approach does not take into account the nonlinear work of soils and, as a result, does not reliably display the base deformations. This, in turn, leads to the fact that the SSS of structures is not determined correctly. Such an approach cannot be considered acceptable, especially for the structures located in difficult engineering and geological conditions [13, 14].

Scientists in these situations use the specially designed models. Let us consider the most widely used soil models with the possibility of taking into account their nonlinear work:

– **Mora Coulomb model (Mohr-Coulomb)**.

The Mohr-Coulomb elastic-plastic model contains five input parameters: \( E \) and \( v \) – are the soil elasticity parameters, \( \varphi \) and \( c \) – are the soil plasticity parameters and \( \psi \) – defines the dilatancy angle.

The Mohr-Coulomb yield criterion has two drawbacks:
– the average principal stress does not affect fluidity, which contradicts the natural behavior of soils;
– the meridian and fracture curve for the Mohr-Coulomb criterion are linear, that is, the strength parameter (internal friction angle) does not depend on the comprehensive compression (hydrostatic pressure) pressure, which also has nothing to do with the real physics of the processes.

Plasticity in this model is associated with the occurrence of irreversible deformations. To determine whether plasticity is encountered in the calculation or not, the yield function \( f \) is defined as a function of stress and strain. Often the yield function can be represented as a surface in the space of principal stresses.
Figure 1. The yield surface in the space of the main stresses (at c = 0): left – Coulomb-Mohr; right – hardening soil

The Coulomb-Mohr model has a fixed yield surface, that is, a surface that is completely determined by the model parameters and which does not reflect plastic deformation. Under the stress conditions represented by the points within the yield surface, the soil behavior is strictly elastic and all deformations are reversible.

– soil hardening elastoplastic model (Hardening Soil).

The hardening elastoplastic model is an advanced model. In this model, as in the Mohr-Coulomb model, the ultimate stress state is described using the friction angle $\phi$, keying action $c$ and dilatancy angle $\psi$.

Soil stiffness is defined by three different input parameters: stiffness under triaxial loading $E_{50ref}$, unload stiffness $E_{uref}$ and stiffness under loading in the odometer $E_{oedref}$. In contrast to the Mohr-Coulomb model, an elastic-plastic model with soil hardening also takes into account the stiffness modulus dependence on stresses. An important role associated with the soil deformation is played by the initial state of the soil, which may be in a state of re-compaction, taking this state into account by entering the coefficient of re-consolidation OCR.

It should be noted that the last two material models presented above are based on the relationship between the rate of change of effective stresses $\sigma$ and the strain rate $\varepsilon$. Such a dependence can be represented as follows:

$$\sigma = M \cdot \varepsilon,$$

where $M$ – is the material stiffness matrix.

In this equation, the stress tensors of stress and strain changes are presented in a vector form and include (for spatial problems) the six Cartesian components:

$$\sigma = (\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{zx}) \quad \varepsilon = (\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{zx})$$

For geometric modeling, various finite element libraries can be used. Various elements can be used for linear and nonlinear calculations of the stress-strain state, consolidation and other types of conjugate calculations. It is important to understand the elements used and their corresponding properties in order to correctly carry out the calculations. In geometric modeling and problem solving, the following types of elements were used:

– one-dimensional element - a lineal element with two nodes, which uses information about the form (distance between nodes). One-dimensional elements include: rod elements and embedded rod elements, beam elements, built-in beam elements, one-dimensional geogrid elements, pile elements and elastic bond elements;

– interface elements – the elements used to model the interaction between surfaces or demarcation lines. Elements of this type include face-to-face contact elements with 6/8/12/16 nodes and line-to-line contact elements with 4/6 nodes;
rigid coupling elements and interpolation elements, respectively the elements of the same name for modeling rigid coupling between nodes and for interpolating relative displacements. The characteristics of these elements are similar to those of multipoint connections;

- two-dimensional element - an element of a triangular or rectangular shape with 3/4/6/8 nodes. A two-dimensional element may be curved in space. Two-dimensional elements include: elements of plane deformation, plane stress state, shell elements, axisymmetric elements of a solid body, two-dimensional elements of a geogrid, and also measuring the shell elements. The plane deformation and axisymmetric elements of a solid are the two-dimensional elements, but are used to calculate the volumetric stress-strain state.

Shell elements may belong to curved surfaces and their nodes may not lie in the same plane. This circumstance should be taken into account when determining the position of the element coordinate system (ECS). In the element coordinate system of a triangular shell element, the direction of the axis \(x\) corresponds to the direction from node 1 to node 2, and the axis \(z\) is directed normal to the plane formed by the directions from node 1 to node 2 and from node 1 to node 3. In the quadrangular shell element, the \(x\) axis is directed along the bisector of the angle formed by the intersection of the element connecting nodes’ diagonals 1 and 3, and 4 and 2, respectively and the axis \(z\) is directed normally to the plane formed by these two diagonals. The shell finite element is formulated in the element coordinate system (ECS). The coordinate system of the shell element is shown in Figure 2.

![Figure 2. The coordinate system of the shell element](image)

The methods for determining the material coordinate system’s orientation for the shell element are the same as those used for the plane stress state elements — the method of the rotation angle relative to the line connecting the element’s nodes 1 and 2 and the projection method of an arbitrary coordinate system.

The solution of the system of equations is carried out by finding the solution \(u\) of the linear system of equations in the form represented by the equation:

\[ Ku = p \]

In this case, the solution of systems of equations is used not only in linear static strength calculation, but in all types of calculations, such as the calculation of proper forms, dynamic calculations, nonlinear calculations, etc. The list of key solvers includes the Gaussian elimination method; a direct solver based on the partitioning method, as well as an iterative solver that converges to a solution that minimizes iterative calculations. For strength calculations, a direct solver is mainly used, since it does not depend on the numerical properties of the matrices and makes it possible to confidently find a solution.

Performing a linear static calculation assumes the presence of linearly elastic properties of the base soil, also the calculation of the base behavior during loading is determined by the static calculation. Soil materials exhibit linear elastic properties only in the early stages of loading corresponding to the appearance of small deformations. However, since the linear-static approach does not imply the onset of fracture and linearly idealizes the ratio of stresses and strains, it is widely used to perform simple
calculations, such as calculating the stresses distribution and finding places of their concentrations in the natural base stress state.

The nonlinear solution for the finite element method is a method of reducing to the correct solution the accumulated step-by-step solutions obtained by the iterative calculations, see Figure 3.

**Figure 3.** The accumulated step-by-step solution and nonlinear finite element reduction

Non-linear static calculation, that is, non-linear-elastic or elastoplastic calculation takes into account all physical phenomena including the non-linearities. The behavior of structures and foundations is no exception. Nonlinear static calculation is used to simulate the base behavior, taking into account the nonlinear behavior when the changes in the system in time are small and can be ignored. This calculation can be used for the following non-linearities:

- **material non-linearity.** Such non-linearity occurs when the relationship between stress and strain is non-linear. Most soil materials exhibit this type of non-linearity;

- **geometric non-linearity.** If the relationship between displacements and deformations is non-linear, but the linear operation assumption is no longer applicable in the case of large displacements or rotations;

- **non-linearity of loads and boundary conditions.** Non-linearity, which includes non-linear contact behavior or non-linearity caused by a change in the load direction depending on the deformation caused by the load, such as a concentrated force.

In order to analyze a number of the considered models, we carried out the elevated structures’ SSS study of the water support structure located in difficult engineering and geological conditions at a real facility. What was the reason for the numerical simulation of the structure in the Stark ES software package? The calculation model is presented in Figure 4.

**Figure 4.** Calculation model of the investigated structure
On the calculation model of the retaining structure, the selection of the design sections presented in Figure 5 was made on the circuit diagram used for further analysis of vertical movements.

![Figure 5. Scheme of design sections](image)

The visualized results of calculating the characteristic vertical movements of the grillage are presented in Figure 6.

![Figure 6. Visualized vertical movements of the grillage](image)
Summary
Analyzing the results, we state that the maximum vertical displacements are numerically equal to 0.055 mm, the vertical displacements in the section 2–2 are 0.032 mm.

At the next stage, an analysis of vertical displacements in the calculated sections was carried out using a specialized geotechnical software package for modeling interactions between structures and their foundations based on the GTS NX finite element method.

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 in the Stark ES PC with the stiffness of the base determined by the Winkler-Fuss model are 0.032 mm.

The presented results make it possible to state that in the case of the water structures’ location in difficult engineering and geological conditions, not only the choice of a design model for the base soil, but also the software package accepted for calculation, preferably specializing in the tasks to be solved, allow obtaining the most reliable, adequate to real conditions results.

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