The water structures’ operability analysis, taking into account damage and certain negative factors

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Abstract. Damage to individual structures or their elements at water structures can lead to irreversible consequences with significant damage and tragedies. The influence assessment degree of the plastic deformations, local subsidence of soil on the structure performance is an urgent task that requires attention.

Introduction
Water structures are used to contain water, which has significant mass and energy. However, over time, these structures can be worn out [1, 2, 3, 4]. The destruction consequences of water structures can be very significant. It is necessary to analyze and monitor water structures for damage to the particular structures. It is possible to analyze the operability of a water support structure under various conditions using modern methods of mathematical modeling. As a result of the analysis, it is possible to determine the safe operation of the structure [5, 6, 7]. If it is impossible to ensure the latter, the development of special measures is necessary. The use of modern automated engineering analysis software products is by far the most effective calculation method for assessing the technical condition of water structures operating in the base – foundation – elevated system [8, 9].

Material and technology
In order to analyze the water structures’ operation, we will carry out its numerical simulation.

The location and characteristic parameters of possible damage to the structure were taken on the basis of an analysis of the work performed on the hydraulic structures’ inspection.

The task to be solved is to identify weaknesses in the water structure and the effect of any of the structures that failed for various reasons on the structure’s performance.

The water structures’ operability analysis was carried out taking into account the following types of damage:
- the formation of plastic deformations’ (cracking) zones in the designs of buttresses under the prolonged load action;
- the formation of plastic deformations’ zones in the water structure under the prolonged load action;
- buttress construction failure;
- local subsidence.

In the process of modeling, the calculation models’ identity was determined by comparing the results with the data obtained during the design, as well as the data obtained from the structure’s monitoring [10, 11, 12, 13, 14]. Numerical solutions of the task were carried out in the software package for calculating the structures for strength, stability and vibrations based on the finite element
The method is STARK ES version 2019 and the specialized geotechnical software complex GTS NX version 2019.

The aim of the work is to analyze the water structure’s operability for various structural damages. The criterion for assessing the structure’s operability is the quantitative and qualitative values of the building structures’ parameters, including the foundation soils’ condition, which meet the requirements established in the design documentation.

Let us consider the type of structural damage in the form of inelastic deformations. With the long-term load action, inelastic deformations of concrete increase over time, that is, the zones of plastic hinges form. The property of concrete, characterized by an increase in inelastic deformations during the prolonged load action, is called creep of concrete.

The development modeling of inelastic deformations under the prolonged load action in the buttress structure was carried out by changing the parameter of the concrete deformation modulus, determined on the basis of the expression:

\[ E_{b,T} = \frac{E_b}{1 + \phi_{b,cr}} \]

where:
- \( E_{b,T} \) – defines the modulus of concrete deformation under continuous load;
- \( E_b \) – is the initial modulus of elasticity;
- \( \phi_{b,cr} \) – is the creep coefficient of concrete.

The nature of creep of concrete is due to its structure, a long crystallization process and a decrease in the amount of gel during the cement stone hardening. Under load, redistribution of stresses occurs with the gel structural component undergoing a viscous flow onto the crystalline intergrowth and aggregate grains. At the same time, capillary phenomena associated with the movement of excess water under load in micropores and capillaries contribute to the development of creep deformations. Over time, the stress redistribution process decays and the deformation stops.

The total displacement calculation results \( (U_{tot} = \sqrt{Ux^2 + Uy^2 + Uz^2}) \) the pressure face of the dam without taking into account the plastic deformations zones’ formation of the water structure are presented in Figure 1.

![Max displacement is 5.87631 mm in knot 8168](image)

**Figure 1.** Complete displacement of the water support structure’s pressure face

Let us simulate the formation of the plastic deformations’ zones in the designs of buttresses under the prolonged load action.

The results of calculating the total displacements of the pressure face in the water structure, taking into account the plastic deformation zones’ formation in buttress structures, are presented in Figure 2.
Max displacement is 6.08604 mm in knot 8168

**Figure 2.** Complete displacement of the pressure face in the water structure (plastic deformations in buttress structures)

Analyzing the obtained results, we note that the plastic deformations in the buttress structures do not significantly affect the displacement of the pressure face. This is due to the absence of tensile stresses in the buttresses’ designs.

Based on the presented data, damage does not have a significant impact on the structure’s performance.

For further analysis, modeling of the plastic deformations’ zones formation in the water structure was carried out under the long-term load. The results of calculating the total displacement of the dam’s pressure face, taking into account the plastic deformations’ zones formation in the construction of buttresses, are presented in Figure 3.

Max displacement is 16.3572 mm in knot 10025

**Figure 3.** Complete displacement of the pressure face of the water support structure (plastic deformations in the water support structure)

A numerical analysis was performed to assess the strength (analysis of the design scheme individual finite elements safety margin for the given loads; the strength of the elements is analyzed by the forces arising from static loads) of the water structures for two design cases:

a) the formation of plastic deformations in the water structure is not taken into account;

b) plastic deformations in the water structure are present.

Next, we evaluate the water structure’s operability during the destruction of some buttress structures. Firstly, we consider the destruction of the buttress located on the central axis of the water support structure.

The design scheme of the water structure during the destruction of the buttress located on the central axis of the water structure is shown in Figure 4.
Figure 4. Calculation scheme of the water structure during the destruction of the buttress located on the central axis of the water structure

The calculation results for the reinforcement of the water structure are shown in Figures 5–8.

**Figure 5.** Top reinforcement along the axis «r»

*Min Asro = 0 [cm²/m],
Max Asro = 17.5486 [cm²/m]*

**Figure 6.** Top reinforcement along the axis «s»

*Min Asso = 0 [cm²/m],
Max Asso = 18.3087 [cm²/m]*

**Figure 7.** Lower reinforcement along the axis «r»

*Min Asru = 0 [cm²/m],
Max Asru = 18.5298 [cm²/m]*

**Figure 8.** Lower reinforcement along the axis «s»

*Min Assu = 0 [cm²/m],
Max Assu = 19.7922 [cm²/m]*

Based on the presented data, we note that when the construction of the buttress located on the central axis of the water structure is destroyed, a slight increase in the required cross-sectional reinforcement area for the upper reinforcement is observed. For the lower reinforcement with such a destruction of the buttress structure, there is also a slight lack of the reinforcement cross-sectional area. It should be noted that the maximum hydrostatic pressure in the plane of the excluded buttress structure is 105 kH/m².

Secondly, we consider the destruction of the water structure’s extreme left buttress.
The design scheme of the water support structure during the destruction of the leftmost buttress is shown in Figure 9.

![Figure 9. Calculation scheme of the water support structure during the destruction of the left buttress](image)

The calculation results of the water structure reinforcing during the destruction of the left buttress are shown in Figures 10–13.

**Figure 10.** Top reinforcement along the axis «r»

\[
\begin{align*}
\text{Min } A_{sr} &= 0 \text{ [cm}^2/\text{m]} , \\
\text{Max } A_{sr} &= 16.0704 \text{ [cm}^2/\text{m]} 
\end{align*}
\]

**Figure 11.** Top reinforcement along the axis «s»

\[
\begin{align*}
\text{Min } A_{ss} &= 0 \text{ [cm}^2/\text{m]} , \\
\text{Max } A_{ss} &= 18.3916 \text{ [cm}^2/\text{m]} 
\end{align*}
\]

**Figure 12.** Lower reinforcement along the axis «r»

\[
\begin{align*}
\text{Min } A_{sr} &= 0 \text{ [cm}^2/\text{m]} , \\
\text{Max } A_{sr} &= 17.7226 \text{ [cm}^2/\text{m]} 
\end{align*}
\]

**Figure 13.** Lower reinforcement along the axis «s»

\[
\begin{align*}
\text{Min } A_{ss} &= 0 \text{ [cm}^2/\text{m]} , \\
\text{Max } A_{ss} &= 19.123 \text{ [cm}^2/\text{m]} 
\end{align*}
\]

Based on the presented analysis, we note that when the design of the left buttress is destroyed, there is a slight increase in the required reinforcement cross-sectional area for the upper reinforcement. For the lower reinforcement during the destruction of the buttress structure provided in stage III, there is also a slight lack of the reinforcement cross-sectional area. It should be noted that the maximum hydrostatic pressure in the plane of the excluded buttress structure is 45 kH/m².
Summary
The analysis of the operability of water structures was carried out taking into account the presence of structural damage. The following types of damage are considered:
- the formation of plastic deformations’ (cracking) zones in the designs of buttresses under the prolonged load action;
- the formation of plastic deformations’ zones in the water structure under the prolonged load action;
- buttress construction failure;
- local subsidence.

The type of damage was revealed in which the performance of the structure is not ensured - the buttress structure’s destruction. Other types of damage do not make a significant contribution to the performance of the structure; operability with these types of damage is provided.

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