Filtration Regimes Calculation of Hydraulic Structures of Alma Reservoir

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Abstract. In the article the Crimean Peninsula is exposed as one of the most problematic areas for providing water resources in the Russian Federation. By 2013, the filling of drinking-water reservoirs due to river runoff and precipitation was at the level of 20-25% of the total design volume and it was the lowest indicator for the last 25 years. In 2014, after the reunification of Crimea with Russia, new hydraulic structures began functioning to supply water to Crimean residents, which allowed filling the North Crimean Canal with water from the Belogorsk and Taigan reservoirs along the Biyuk-Karasu riverbed and eastern Crimea residents began to receive water. The average population density of Crimea is 85 people / km². The average long-term value of water resources for this territory is 1.0 km³/year, and one resident - 432 m³/year, which is the lowest of all the constituent entities of the Russian Federation. Much attention is paid to the safety of operating reservoirs, including the oldest one in Crimea - Alminsky reservoir. The calculations are given and filtration strength of the dam body soils of reservoir is estimated: specific filtration flow rates, filtration flow outlet velocity and effective pressure gradients. Calculation of the filtration regimes of the dam construction was carried out for two loading cases: main and special load combination. The obtained data indicates that actual parameters of the dam construction provide filtration strength and structure reliability under the accepted loading cases.

1. Introduction

Until only a short time previously Ukraine provided up to 85% of Crimea’s fresh water needs through the North Crimean Canal, which was used to irrigate about 140 thousand hectares of farmland. By 2013, filling volume of reservoirs for drinking purposes, impounded due to river runoff and atmospheric precipitation, was at the level of 20-25% of the total design volume, which turned out to be the lowest indicator in the last 25 years. After the reunification of the peninsula with Russia, water supply through the canal was completely stopped. In 2014, hydrotechnical structures were built to provide water to Crimean residents, which made it possible to fill the North Crimean Canal with water from the Belogorsk and Taigan reservoirs along the Biyuk-Karasu riverbed. Thanks to this engineering solution, residents of the eastern Crimea began to receive water. At the end of 2014, construction began on three more water intakes in the Nizhnegorsky and Dzhankoysky districts - Novogrigoryevsky, Nezhinsky and Prostornensky with a total debit of about 200 thousand cubic meters per day, their construction was...
completed in the fall of 2016 [1]. The average population density of Crimea is 85 people / km$^2$. The long-term average water supply value for this territory is 1.0 km$^3$ / year, and water supply per inhabitant is 432 m$^3$ / year, which is the lowest of all constituent entities of the Russian Federation.

Alma reservoir in Crimea is the oldest of the existing ones. According to the project of the Crimean Water Management Farm, the first construction phase was completed in 1929, the second - in 1934. It is located in the Bazar-Dzhilga beam, filled with water from the Alma River through a 5-kilometer-long-canal. The reservoir is considered to be one of the best in Crimea in terms of water quality, which is why they try not to use it for irrigation. However, water balance of the valley is not perfect at the moment. For example, in 2011, population of several villages was seriously concerned with village wells drying [2]. The Alminskoe reservoir has been operating for about 90 years and therefore the assessment of its strength, stability and operational reliability is a vital task. The purpose of the study is to assess the filtration strength of the soil of the dam body of the Alma reservoir.

2. Research objectives
- establish the design profiles of the structure, the filtration coefficient in individual elements of the dam body $k_d$ and its foundation $k_w$;
- determine the position of the depression curve and establishment of gradients and velocities of the filtration flow;
- determine the filtration stability of the soil (heaving and suffusion), identify velocities values and gradients of the filtration flow when it enters the lower pool or into drainage structures. Materials and methods. The earth dam of the Alminsky reservoir has: length 220 m, height 20.2 m, width along the ridge 7.45 m. The length of the reservoir is 1.25 km; maximum width - 950 m; maximum depth - 13.8 m; average depth - 12.5 m; mirror area - 86.8 ha. When calculating filtration strength of the soils of the body dam of the Alma reservoir, we were guided by the following rules and methods: P 71-2000 VNIIG “Recommendations for the diagnostic control of the filtration regime of soil dams” [3]. In hydraulic engineering, when considering filtration, we mean porous media formed from soils (cohesive and incoherent), fractured rocks, concrete and other porous materials, and water is considered as a filtering liquid [4]. Due to the lack of regularity in the shape of pores and cracks, averaged characteristics of the filtration properties of a porous medium are considered [5].

3. Research results
The calculation of the filtration regimes of the Alminsk reservoir dam construction was carried out for two loading cases: main (USL mark (upstream level) = NBL (normal backed level)) and special (USL mark = FBL (forced backed level)) load combination. Distinguish local (normal) total or casual (random) filtration strength of soils. Local (normal) soil strength is determined in the area where the filtration flow exits in the dam body into downstream or at the contact of fine-grained and coarse-grained soils of the base and body structure, can be estimated using calculations based on the rules of mechanics. The casual strength of soils is determined in some places of the dam's longitudinal profile or anti-filtering elements, which can be violated in places of the longitudinal profile of the structure, and design conditions for evaluating in such places soil strength can be random in nature [6]. In the calculations, it is necessary to ensure that:

$$J_{\text{max}} \leq J_{\text{m.k}}$$

Where $J_{\text{max}}$ – actual gradient, determined approximately; for the base of the structure this actual gradient is determined by the formula $J = \frac{h_1 - h_0}{n_{bw}}$,

- $J_{\text{m.k}} = 1.5$ – minimum permissible controlled gradient for the dam body.
- $J_{\text{m.k.o}} = 1.5$ – minimum allowable controlled gradient for the base.
- $J_{\text{m.k.o}} = 12.0$ – minimum allowable controlled gradient for the dam screen [7,8].

If it is not performed conditionally $J_{\text{max}} \leq J_{\text{m.k}}$, then it is necessary to select the dam parameters or to perform the installation of an anti-filtration element in order to ensure acceptable gradients.

The input materials for filtration calculations were the following:
- accepted cross section of the dam;
- physical mechanical properties of soils composing body and foundation of the structures [9];
- water levels in the Alma Reservoir for main (with USL mark = 180.20 m) and special (with NBL = 180.84 m) load cases (Fig. 1).

![Scheme for soils calculation for filtration strength](image)

**Figure 1.** Scheme for soils calculation for filtration strength a) in the body of the structure; b) at the base of the structure.

In the lack of water in the downstream, calculation of the drained dam with a screen is carried out according to these formulas:

\[
q_t = \frac{k_t}{k_r} \frac{H^2 - h^2 - z_0^2}{2\delta_{cp} \cdot n \cdot \sin \theta},
\]

where \( n = \frac{k_t}{k_r} \);
\( h \) – depth of filtration flow directly behind the screen;
\( z_0 \) – vertical projection of the average screen thickness;
\( \theta \) – inclination angle of the screen to the dam base;
\( \delta_{cp} \) – average screen thickness.

\[
z_0 = \delta_{cp} \cdot \cos \theta.
\]

\[
q_t = \frac{h^2}{k_r},
\]

The horizontal projection of the depression curve is calculated by the formula:

\[
L_d = m_1 (H_w - h) + b_w + m_2 (H_w - h_d) - m_3 h_d + e - \frac{\delta_{cp} + t_{cp}}{\sin \theta},
\]

where \( t_{cp} \) – is thickness of the protective layer;
\( e \) – is the figure of the depression curve entering the drainage.

\[
e = (0.05 + 0.06)h.
\]

Depression curve calculation is made according to the formula:

\[
y^2 = \frac{h^2}{L_d} x.
\]

The screen is located near the pressure slope (Fig. 1). The screen thickness at the top \( \delta_v \) should be at least 0.8 m, and at the bottom \( \delta_n \geq 0.1 \text{Npl} \), but not less than 2.0 m. The screen is covered with a protective layer with a thickness of the upper part of the dam about 1.0 m and at the sole about 2.0 m, but not less than the freezing depth [10]. Due to the fact that the design and executive documentation
for the construction of the hydraulic system of the Alminsky hydroelectric complex was lost, unknown values in the calculations were assigned in accordance with the regulatory literature and recommendations for design, construction, and operation of similar hydraulic structures.

We adopt the convention that 
\[ \delta_{\text{av}} = 2.0 \text{ m}, \delta_{\text{m}} = 5.0 \text{ m}, \]
\[ t_{z_{\text{m}}} = 1.0, t_{z_{\text{m}}} = 2.0 \]
and further calculate:
\[ \delta_{\text{cp}} = \frac{\delta_{\text{av}} + \delta_{\text{m}}}{2} = \frac{2.0 + 5.0}{2} = 3.5 \text{ m}. \]
\[ t_{z_{\text{cp}}} = \frac{t_{z_{\text{m}}} + t_{z_{\text{m}}}}{2} = \frac{1.0 + 2.0}{2} = 1.5 \text{ m}. \]
\[ z_{0} = 3.5 \cdot \cos 20^\circ = 3.5 \cdot 0.94 = 3.29 \text{ m}. \]

To simplify the calculations, we adopted a screen with a width \( \delta_{\text{av}} \) with an inclination angle \( \theta \) equal to the inclination angle of the uphill slope. Given values of \( h \) at least three times, \( L_{d} \) was calculated according to the equation (4). Designating the right side of equation (1) as \( F_{1}(h) \) and the right side of equation (3) as \( F_{2}(h) \), their values are calculated. For a dam with a filtration coefficient \( k_{\text{f}} \) on an impenetrable foundation with a filtration coefficient \( k_{\text{o}} \), the problem is considered under two assumptions:

1) permeable dam, impermeable base;
2) impermeable dam, permeable base. Based on the first assumption considered, the specific filtration flow rate \( q_{t} \) through the dam body of the Alminsky reservoir was obtained. The specific filtration rate through a water-permeable base is calculated by the equation:
\[ q_{0} = \omega \cdot V, \]
\[ \omega = T \cdot 1, \]
\[ J = \frac{H_{1} - h_{0}}{nB_{w}}, \]
thereafter
\[ q_{0} = \frac{k_{0}T(H_{1} - h_{0})}{nB_{w}}. \]

while \( n \) – the correction factor determined depending on the ratio \( B_{w}/T \) according to the table 1.

Table 1. the correction factor value \( n \).

| \( B_{w}/T \) | 20    | 5     | 4     | 3     | 2     | 1     |
|-------------|-------|-------|-------|-------|-------|-------|
| \( n \)     | 1,15  | 1,18  | 1,23  | 1,30  | 1,44  | 1,87  |

If there are dissimilar soils at the base of the structure, the averaged filtration coefficient \( k_{\text{avg}} \) is recommended to use, characterizing the total water permeability of the formation \( T \). The formula, and accordingly, the average coefficient \( k_{\text{avg}} \), depends on the flow direction relative to the occurrence of the aquifer.

\[ T = T_{1} + T_{2} + \ldots + T_{n}. \]

The maximum \( k_{\text{max}} \) value will be parallel to the bedding during water filtration and the minimum value \( k_{\text{min}} \) will be perpendicular to the bedding:
\[ k_{\text{cp}_{\text{max}}} = \frac{k_{1}T_{1} + k_{2}T_{2} + \ldots + k_{n}T_{n}}{T_{1} + T_{2} + \ldots + T_{n}}, \]
\[ k_{\text{cp}_{\text{min}}} = \frac{T_{1} + T_{2} + \ldots + T_{n}}{k_{1} + k_{2} + \ldots + k_{n}}. \]

The average filtration coefficient is calculated by the formula:
\[ k_{\text{avg}} = \sqrt{k_{\text{cp}_{\text{max}}} \cdot k_{\text{cp}_{\text{min}}}}. \]

To calculate the filtration flow rate \( q_{0} \) at the dam base from different soils, the average filtration coefficient \( k_{\text{avg}} \) is introduced instead \( k_{0} \). Thus, the total specific filtration rate is:
\[ q = q_{t} + q_{0}. \]
The input materials for filtration calculations were:
- taken cross-section of the dam;
- physical mechanical properties of soils composing the body and foundation structures;
- water levels in the Alminskoe reservoir for the main (with NBL = 180.20 m) and special (with FBL = 180.84 m) loading case. The calculation results for determining the filtration modes of the structure are presented in table 2.

Table 2. Calculations results of the filtration flow in the body and through the base structures.

| Calculated parameter                                      | Settlement cross-section on Station1+60 |
|-----------------------------------------------------------|-----------------------------------------|
|                                                           | NBL          | FBL          |
| Estimated filtration path length, L, m                   | 60,90        | 60,05        |
| Filtration depth behind the screen, h, m                 | 5,61         | 5,90         |
| Specific filtration rate through the dam body, \( q_s \), \( m^3/\text{day per rm} \) | 0,173        | 0,194        |
| Specific filtration flow rate at the base, \( q_0 \), \( m^3/\text{day per rm} \) | 0,171        | 0,180        |
| Total specific filtration rate, \( q \), \( m^3/\text{day per rm} \) | 0,344        | 0,374        |
| The filtration flow exit velocity at the base, \( V_0 \), \( m/\text{day} \) | 0,043        | 0,045        |
| The actual gradient of the filtration flow for the screen, \( J_{scr} \) | 2,254        | 2,371        |
| The actual gradient of the filtration flow outlet at the base, \( J_b \) | 0,086        | 0,090        |

The calculation results determining the parameters of the filtration flow in the dam body and through the base show that the actual parameters of the structure provide its filtration strength and reliability in the accepted design cases. The design diagram with the depressed curves plotted on the obtained coordinates is presented in Fig. 2.

![Figure 2. Filtration calculation scheme through the Alma reservoir dam.](image)

4. Conclusion
The calculation results determine the specific filtration flow rate, the filtration flow outlet velocity and the existing pressure gradients indicate that the actual parameters of the Alminsky reservoir dam provide filtration strength and reliability of the structure under accepted loading cases. It is recommended to develop and implement a project to clear the reservoir bed from bottom sediments which have accumulated during the operation period (about 90 years), in order to increase the useful volume of the Alma reservoir, which is used for irrigation purposes. In order to carry out proper monitoring, obtain reliable and sufficient data on the filtration flow in the dam body of the Alminsky reservoir, bypassing
and at the base of the structure, it is therefore recommended to develop and implement a project for the construction of a piezo metric network.

5. References

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