Variants of mathematical modeling of hydraulic conditions of coupling of the pools of drainage structures of the Krasnodar reservoir on the Kuban river

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Abstract. The article deals with the main parameters of the application of modern methods of mathematical modeling of hydraulic conditions of coupling of the pools of drainage structures of the Krasnodar Reservoir on the Kuban River. The thirty-five-year period of operation of the Krasnodar reservoir and its structures showed that the washouts of the Kuban River bed in the lower reaches significantly exceeded the forecast assumptions. The decrease in water levels in the Kuban river led to a deterioration in the hydraulic regime of the pools of drainage structures. During the period of operation, deformation processes occurred in the channel of the highly unpredictable the Kuban river, which led to a decrease in water levels of more than two meters in relation to the initial data at the time of design and construction. There was a danger of violation of the hydraulic conditions of the coupling of the pools of drainage structures - providing the necessary conjugated depth of the perfect hydraulic jump and, consequently, preventing it from jumping out of the water well. In the latter case, there would be disastrous consequences.

1. Introduction

The construction of the Krasnodar reservoir began in 1967. It was in temporary operation from June 27, 1973 to October 22, 1975. It has been in permanent operation since December 4, 1975 [1].

When developing the project of the construction of the Krasnodar reservoir, the results of scientific hydraulic studies conducted on the instructions of the “Kubangiprovodkhoz” Institute in the hydrotechnical scientific laboratory on three models (two spatial and one flat) and in the laboratory of the “Yuzhgiprovodkhoz” Institute on an air model were taken into account.

In the course of research, the results obtained were systematically brought to the attention of design and construction organizations, discussed together with them and, if necessary, changes were made to the conditions of conducting experiments, as well as to some structural forms of structures [2].

In accordance with the need for further development of the national economy, considerable attention was paid to the construction of the Krasnodar reservoir in the sixties of the XX century. The main purpose of the Krasnodar reservoir was to provide water to rice farms in Kuban. In addition, it was supposed to reduce to a minimum the number of destructive floods in the lower reaches of the Kuban river [3].
Simultaneously with these two main goals, the Krasnodar reservoir is designed to solve many other tasks, such as a comprehensive state plan event [4, 5].

For example, the construction of the reservoir with a volume of 3.1 billion m$^3$ allowed us not only to enter 250 thousand hectares of new rice areas into economic turnover and cut the peak of the flood from about 2400 m$^3$/s to 1500 m$^3$/s, but also to improve the conditions of navigation on the Kuban River, develop a suburban irrigation system to meet the needs of the city in vegetables and fruits, improve the water supply of the city of Krasnodar and provide the possibility of performing other measures to improve the welfare of workers (sanitary, sports, fisheries, etc.) [6]. The Krasnodar reservoir is located in the middle reaches of the Kuban River in 248 km from its mouth directly above the city of Krasnodar.

The useful capacity of the reservoir (on the project) is 2160 million m$^3$, the flood control capacity is 652 million m$^3$. The reservoir capacity at the normal retaining level (33.65 m) is 2396 million m$^3$. It is 35.23 m or 3048 million m$^3$ with FU (0.1 %). With the aim of reducing the negative influence of the Krasnodar reservoir on the adjacent territories, in 1993 the Republic of Adygea and Krasnodar Territory signed the agreement on reducing NRL (normal retaining level) on 0.9 m below the design project (to the level of 32.75 m). At the same time, the useful capacity of the Krasnodar reservoir decreased by 425 million m$^3$ (that is, by 20 %). The Krasnodar reservoir protects the lower reaches of the Kuban River from floods for more than 30 years, provides a guaranteed supply of water to irrigation systems, including rice, improves water supply to the population of the region, navigation and fish passage [7].

2. Materials and methods

The area of the Krasnodar reservoir includes the Tschikskoe reservoir, built in 1941 at the mouth of the Belaya river, with a mirror area of 9.5 thousand hectares. The water supply of the Krasnodar reservoir extends along the Kuban River to Ust-Labinsk, along the Pshish River to the village Teuchezh-Habl and along the Psekups River to the village Saratovskaya. In the spring-summer period, water from the reservoir floods the systems of the Azov-Kuban estuaries: Kulikovo-Kurchansky, Kiziltashsky, Chernoorlovsky, Akhtarsko-Grivensky. The part of the dam is a fish passage structure – mechanical fish ladder for passing migratory fish – sturgeon, vimba, shemai. In spring and summer fish pass from the lower pool to the upper one to spawning grounds in the upper part of the Kuban River – the Psekups, Pshish, Laba, Belaya Rivers. The ichthyofauna of the Krasnodar reservoir is mainly represented by fish living in the Kuban River. The main fish are the following: gustera, bream, carp, walleye and herbivores - catfish, pike, asp, barbel, roach, and bleak. The 4850 ha of fishing areas have been prepared for commercial development of the reservoir [8].

Systematic observations have shown that the decrease in water levels behind spillway structures is from 0.1 to 0.05 m per year, and by 2002 this decrease was more than 1.7 m. The repair and restoration works carried out in 2002 – 2003 on the reconstruction of the lower stream permitted to solve the problem for a short period of time.

From 1977 to 1979 the hydraulic studies on enhancing the reliability of spillway structures through structural modifications on the apron behind the stilling basins were conducted in the laboratory of engineering hydraulics of Novocherkassk Engineering-Ameliorative Institute to ensure the calculated mode of the conjunction of downstreams due to a sharp decrease of water levels in the Kuban River according to the forecast for 1982 [9, 10]. The spillway structure is embedded in an earthen dam between PK 113+35 and PK 114+35. The estimated capacity of the spillway structure, consisting of four holes with a span of 10 m each with practical spillways together with a fish lift according to the project, is 1500 m$^3$/s [11].

The spillway of the Krasnodar reservoir is a four-span concrete structure, which includes a supply channel, practical spillways, a water well, an apron, and a discharge channel. The supply channel is made of a trapezoidal cross-section with a width of 100 m along the bottom and the laying of slopes in 1:3. The height of the channel is 6.0 m, the bottom and slopes of the channel are fixed with a stone sketch. At the junction of the supply channel with the reinforced concrete entrance part, a tooth made
of stone is arranged to a depth of 3.0 m. The entrance part in the plan has the shape of a bell with vertical reinforced concrete walls. The ponur (bottom plate) has a slope towards the spillway as \( i=0.027 \).

The next component of the spillway is a practical-profile spillway through which water flows. This spillway has a curved drain part, constructed according to data of Krieger-Ofitserov and with a vertical pressure face [12]. This spillway belongs to the vacuum-free outlined along the contour of the lower surface of the incident medium. The flow coefficient is equal to \( m=0.504 \).

The spillway consists of four ten-meter spans and the same width of the fish pass (fish lift), which is located in the center of the water discharge structure. The mark of the spillway crest according to the project is 23.50 m, the bottom behind the spillway (bottom of the water well) is 11.00 m, i.e. the height of the spillway with the NB is 12.50 m, respectively.

During the period of operation, the maximum discharge rates ranged from 594 m\(^3\)/s to 1395 m\(^3\)/s, and the average monthly discharge rates ranged from 498 m\(^3\)/s to 1122 m\(^3\)/s. The minimum discharge costs over the years of operation ranged from 60 m\(^3\)/s to 580 m\(^3\)/s.

The thirty-five-year period of operation of the Krasnodar reservoir and its structures showed [13, 14] that the washouts of the Kuban River bed in the lower reaches significantly exceeded the forecast assumptions. The decrease in water levels in the Kuban River led to a deterioration in the hydraulic regime of the spillway structure. Hydraulic calculations and the results of field studies on the spillway structure indicate that the driven hydraulic mode is observed at flow rates of more than 850 m\(^3\)/s with four working holes and at flow rates of more than 150 m\(^3\)/s - with two working holes at NPU equal to 33.65 m.

The design of the hydraulic mode is the formation of a perfect hydraulic mode as an effective dampener of excess kinetic energy which is disrupted due to a drop in the water level behind the structure. Water flow without a hydraulic jump can release the water at high speeds, causing washouts in the downstream [15].

The main factors determining the stability of hydraulic structures against dangerous washouts in the downstream and in the design of the underground outline of flutbets are the following [16]:

- the correct assignment of the main dimensions of water-cutting devices (for example, the depth and length of a water-cutting well), depending on the combination of unfavorable levels and dangerous water flow rates, possible combinations of gate maneuvering in multi-span structures, structural forms of input and output mating devices, and others, and, of course, the correct choice of calculation formulas and their skillful application [17];
- the layout of the underground circuit, which determines the values of hydrodynamic pressures, on which all other calculated filtration elements (velocities, flow rates, gradients) depend;
- linking the dimensions of individual elements and the entire hydraulic structure as a whole, taking into account the two previous requirements.

Studies have shown that, in most cases, design organizations do not follow the recommendations, contained in literature and training manuals, or distort them.

With regard to filtration calculations, it can be said that despite the numerous and very useful works carried out by many authors on the interpretation of the theory of academician N. N. Pavlovsky and its implementation in practice, there are still no methods of determining hydrodynamic heads acceptable for computational practice according to some simple schemes of the underground circuit.

All this has determined the need to make a number of specific proposals to restore the rights of existing and change some well-known recommendations in order to ensure a more correct assignment of main dimensions and design of individual elements of critical parts of structures and the layout of their combinations as a whole.

Among the issues to be covered on the basis of experience and analysis of existing structures and phenomena are the following [18]: design of water wells on non-rock foundations as the most effective and reliable extinguishing devices; design of fish-passing structures and devices; filtration calculations.

During the period of operation, deformation processes occurred in the channel of the highly
unpredictable Kuban River, which led to a decrease in water levels of more than two meters in relation to the original 1967 (at the time of design and construction). There was a danger of violation of the hydraulic conditions of the interface of the spillway structure, providing the necessary conjugation depth of the perfect hydraulic jump and, consequently, preventing it from jumping out of the water well. In the latter case, there would be disastrous consequences.

To improve the reliability of the spillway structure, appropriate scientific studies were carried out, which made it possible to give a number of recommendations for ensuring the flooding of the hydraulic jump in the water well through the use of an electric fish barrier threshold and an additional threshold behind the water well [19].

As a result of analytical calculations for an expanding water well, as well as hydraulic studies of dam structures of the Yumaguzinsky hydroelectric complex, it was found that, in contrast to studies applied to a flat problem, a smaller depth is required behind the well to ensure the design mode. In addition, both the threshold of the electric fish barrier and the electric fish barrier itself contribute to improving the reliability of the coupling of flows in the downstream.

Calculations and laboratory studies may contain errors inherent in the one-dimensional stylizations of the spatial flow from which these techniques were derived. In addition, these methods do not assess the asymmetry of the hydraulic jump and the possible failure of the flow in the downstream of the hydraulic unit.

The research is a preliminary in nature, designed to demonstrate the possibilities of three-dimensional hydrodynamic modeling in the study of open flows in a region with a complex geometry. The results of the numerical experiment are presented in the form of figures with spatial three-dimensional and flat images of velocity vector fields, plots of averaged velocities and depths. In all the studies performed, the effect of the electric fish barrier threshold was not taken into account (Figure 1).

![Figure 1](image.jpg)

**Figure 1.** Hydraulic jump. Top view of the free surface: a – flow \( Q = 60 \text{ m}^3/\text{s} \); b – flow \( Q = 200 \text{ m}^3/\text{s} \).

It is possible to estimate reliably the spatial conditions of the coupling of the bays by means of a numerical experiment using a hydrodynamic model based on a system of the three-dimensional evolution Navier-Stokes equations [20].

The analysis of the conducted experience shows the following: the hydraulic jump is flooded due to the operation of only two extreme discharge spans, horizontal rotation of the flow and its redistribution within the water well are observed. Waves on the surface outside the water well are insignificant and spread along the entire length along the fish lift (Figure 1).
Figure 2. Pairing of pools. Axonometry. Time – averaged, vertical average velocity vectors: a – flow rate $Q = 60 \text{ m}^3/\text{s}$; b – flow rate $Q = 200 \text{ m}^3/\text{s}$.

As a result of studying figure 3, we can draw the following conclusion, the hydraulic jump is slightly pushed over the spillway. In the water well, the energy of the flow is damped (due to the rotation of the jump and the creation of macro-turbulence). Disturbances of the water flow on the surface of the well and on the apron are insignificant. Eddies are marked within the water well.

Figure 3. Distribution of the averaged longitudinal velocities in the horizontal plane at a distance of 0.2 h from the bottom: a – flow rate $Q = 60 \text{ m}^3/\text{s}$; b – flow rate $Q = 200 \text{ m}^3/\text{s}$.

3. Conclusion
Numerical experiments performed for the first time, using a hydrodynamic model of the spillway of the Krasnodar reservoir hydroelectric complex, are based on a three-dimensional system of the Navier-Stokes evolution equations. According to the considered calculation cases, the following conclusions can be drawn that the damping of the upstream energy occurs in the form of an oblique hydraulic jump. There is a pressure of the jet to the walls of the fish pass.

The reason of the failure can be the development of a jump in the asymmetric water breaking part. According to the design decision, the symmetrical plan of the spillway water well with expanding walls is divided by the fish passage into two parts that are not symmetrical in a cross-section. Another
reason for the failure seems to be an increase in flow through the central spans due to a decrease in a lateral flow compression compared to the extreme side spans. The asymmetry of the jump generates a flow failure in the well and on the apron and further in the discharge channel with the formation of stable eddy currents that can provoke washouts of the bottom of the downstream.

Peculiarities of the flow in an existing design of waves lead to the fact that the main stream flows to downstream along the walls of the fish pass and creates the worst conditions for getting passing fish in the fish pass, which directly contradicts the objectives of the device uniform across the width of the flux distribution pursued in the design.

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