Diagnostics of the Donskoy sluice system in the face of growing water scarcity

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Abstract. The article considers the options of applying numerical methods of technical diagnostics of the Don sluice system in current conditions of growing water scarcity. Studies have shown that a multi-factor survey is the basis for preparing the structure to the extension of its service life. The reliability and failure-free operation of the hydraulic structure is determined from the condition of the state of performance or failure. The existing methods of inspection of hydraulic structures are aimed at assessing the overall suitability of the load-bearing structures of buildings for further operation. Diagnostics is carried out taking into account the current regulatory documents on design and the specifics of operation. Numerical simulation allows us to estimate the influence of a number of factors on the reliability of the Don sluice system.

1. Introduction

Waterways in Russia were a powerful natural factor influencing the development of complex social and economic processes in the second half of the XVIII — early XIX centuries. The study of river routes as the most important part of the transport network was necessary for the analysis of various types and forms of economic activity and the natural geographical environment in Russia.

The history of sluicing of the Lower Don begins with the projects of N. P. Puzyrevsky, compiled on the basis of surveys under his leadership in 1906 ... 1909 [1]. The construction of the Don sluice system was started in 1913. First of all, the Kochetovsky hydroelectric complex was built (according to the scheme of N. P. Puzyrevsky - this is No. 3) [2]. It was extremely necessary for the normal functioning of the North-Donetsk water system and in this system it was No. 1. The history of its construction and the stages of reconstruction are described in detail in the book published by the publishing house of the journal "Vestnik of Transport" in 2009, which is called: "Construction No. 1 on the Don. The new life of the Kochetovsky hydroelectric complex" [3].

According to the data of the Water Cadastre of the Russian Federation for 2014 (Surface and underground water resources, their use and quality) there is a long-term catastrophic decline in total water resources in the south of the Russian Federation. In the Southern Federal district as a whole, the deviation of water resources from the long-term average was -17.2 % compared to - 6.5 % in 2014 [4].

According to the results of visual inspection, about 1/3 of hydraulic structures in Russia need to be restored, since the design of their lifespan up to 30 years and most of the buildings have already...
exhausted their resources, and a further increase in age leads to a decrease in reliability and security, HESs, which are in operation for more than 25 years [5], regardless of the state must once in 5 years to be complex analysis with an assessment of their strength, stability and reliability. The comprehensive analysis of the structure’s state is made in a special manner based on the actual physical-mechanical characteristics of the structures’ materials and their grounds (SP 58.13330.2012 Waterworks. Basic provisions. Updated version of SNIP 33-01-2003, paragraph 6.5) [6].

In recent years, water problems have significantly worsened due to anthropogenic changes in river flow and changes of owners of hydraulic structures [7], such as reservoirs, water intake, spillways, culverts. They are reluctant to invest in the operation of hydraulic structures, improving their reliability and safety. In the most populated areas of the country, there are no large rivers left undamaged by economic activity, both in the catchments and in the riverbeds.

The object of the study is the Donskaya sluice system using modern non-destructive testing devices, namely, the developed software and hardware complex for conducting operational monitoring of the technical condition of hydraulic structures [8], which is designed to determine the parameters of various defects and damages, as well as to calculate the predicted life of their elements. The complex also makes it possible to assess the influence of a number of factors on the reliability of individual elements of the structure, and filtration, abrasion, leaching processes and the degree of wear in areas with different hydraulic characteristics are specific features [9].

The subject of the research is finite element models of the collapsible dam - Poare farm, which makes it possible to calculate the operability of the hydraulic structures of the Don sluice system.

The scientific novelty of the research lies in the development of options to solve the problem of high-quality monitoring of hydraulic structures for assessing the change in the stress-strain state over time under various combinations of loads which were applied to the hydraulic structures of the Don sluice system.

The purpose of the multi-factor survey of hydraulic structures of the Don sluice system is to assess the actual technical condition of the main equipment, determine the residual resource of their elements, as well as establish safety deficiencies to assess the possibility of continuing operation beyond the designated (or 25-year) service life, namely, operation performance. The results of the multivariate survey are the basis for preparing the structure for the extension of its service life.

2. Materials and methods

The water management situation on the Lower Don is largely determined by the possibilities of long-term regulation of the Tsimlyansk reservoir (Wf. = 23.680 million m³, Wf.=11.540 million m³, Fm=2.702 km², annual useful water output W=12.471 million m³). The reservoir fulfills a complex task (navigation, water supply, irrigation and drowning, fish farming). The leading water user is shipping. The volume of cargo transportation along the Lower Don has decreased from 1.31 million tons to 8-10 million tons in recent decades [10].

The irrevocable water consumption in the Lower Don basin is estimated to be 3.37 km³ by the North-Caucasus Scientific Research Institute of Water Management[11]. Taking into account the evaporation losses from the surface of the Tsimlyansk reservoir (on average it was 1.5 km³/year for many years), the value of irrevocable water consumption will increase to 4.87 km³. Navigation releases to the lower reaches of the Tsimlyansk hydroelectric complex under standard operating conditions (410 m³/s) and the current navigation duration (240 days) will require a volume of water in the amount of 8.5 km³. The implementation of the sanitary discharge in the inter-navigation period with a standard flow rate of 230 m³/s will amount to another 2.48 km³ of water. Even taking into account that the flow from the Tsimlyansk dam to the mouth of the river is about 5 km³, we can see how tense the water balance of the reservoir is 10.85 against 11.54 km³ of the useful volume. In fact, in recent years the Tsimlyansk reservoir is filled to the NRL less and less, and it can be stated that this balance will be in short supply. According to preliminary data of the Russian Hydrometeorological Center, low water was expected in 2017, especially on the Lower Don [12], it was predicted from 7 to 9 km³, instead of standard 11.1 km³.
It is possible to reach the guaranteed depths of the shipping route on the lower Don (3.8 – 4.0 m) only by retaining the levels (sluicing). Other various methods known in hydraulic engineering for increasing the minimum depth in the river such as deepening the bottom by dredging, removing rapids in certain sections of the channel, straightening the channel with the help of regulatory structures, releases from higher reservoirs, are ineffective for the conditions of the Lower Don [13].

In 1974, waterworks with a sluice were built near the village Nikolaevskaya. The need for its construction was associated with providing navigable depths at the site of exit from the bottom of approach channel lock No. 15 of the Tsimlyansk dam to the alignment of the Nikolaevsky waterworks. The current pressure is 3.8 – 4.0 m. At the Kochetovsky and Nikolaevsky hydroelectric units, the complex dams (Poare farms) [14] allow us to adjust the amount of backwater and ensure the passage of high water without backwater of the water level in the Don [15].

The Konstantinovsky hydroelectric complex (the unfinished complex in the 1910s according to the scheme of N. P. Puzyresvky) was put into operation in 1982 and began to provide navigation on the 43-km section from the Nikolaevsky hydroelectric complex to the Konstantinovsky hydroelectric complex.

A special feature of this hydroelectric complex (in comparison with the Kochetovsky and Nikolaevsky) is the creation of a year-round (permanent) backup. Amelioration managers of Yuzgiprovodkhoz (now-Yuzhvoproekt) by the example of the Kagal floodplain area showed that the construction of the drainage system in the area of 30 thousand hectares could not prevent ground flow from the upper tail of the Konstantinovsky dam, salinization and waterlogging of the floodplain; the very productive ground was flooded by the unprofitable fish ponds. The same is expected for land in the zone of influence of the future Bagaevsky hydroelectric complex, if the level support is not removed at least during the autumn-winter low water period [16].

The section of the Lower Don from the Kochetovsky hydroelectric complex in the mouth is essentially a river in a free state with a modified hydrological regime in 45 rifts which are separated by short millpond valleys in the segment with a length of 164 km. Despite the large volume of dredging, some of the rifts have retained their typical channel formations – sidewalls, ridges. Due to the limited width of the ship’s course and the sharp turns of the channel, this section is difficult for navigation.

The project of sluicing the Don River, compiled by N. P. Puzyresvky on the basis of surveys of 1906 – 09, was aimed at improving the conditions of navigation on the Don from Kalach to Rostov for 500 miles (~ 533 km).

The gateway project of the Don River by N. P. Puzyresvky implied to reach navigable depths by means of the device of complex dams blocking the river, and it was proposed to arrange chamber locks for the passage of ships from one place to another. The maximum draft of ships after the implementation of works to improve the Don River was supposed to be 2.75 m (9 ft). For the river fleet of that time, the project adopted the following sizes of vessels: useful length-120 fathoms (~ 256 m); width in the light – 15 fathoms (~ 32 m).

The construction of the Don sluice system began with the construction of the Kochetovsky hydroelectric complex (according to the scheme of N. P. Puzyresvky, No. 3), and it was No. 1 in the North-Donetsk water system. Already in the 50-60s of the twentieth century, after the operating of the Volga-Don Channel and in connection with the increase of new ships in size, the old Kochetovsky sluice required reconstruction. Its dimensions became a serious obstacle to navigation, as the new generation of vessels, reaching a length of 130-140 meters, did not fit into the sluice chamber simply. Major works of the project of the institute "Giprechtrans" were started in the mid-50s and were completed mainly in 1969. As a result, the sluice was brought into full compliance with the dimensions of the same structures of the Volga-Don Channel. The same years the three-span spillway dam with a fish-passing sluice was built on the site of the additional hole in the Kochetovsky hydroelectric complex. The upper and lower docks were built, the machinery buildings with a central control panel were made, the chamber parapets were added, and the sluice's electromechanical equipment was replaced [17].

By the 1990s, the Kochetovsky hydroelectric complex was obsolete. The further expansion of the
dimensions of the old sluice chamber is considered irrational. It was more profitable to build a new modern sluice of standard dimensions next to the old chamber, which would take over the main flow of large vessels. In April 2008, the first cargo ship passed through the new sluice [18].

In 1974, a sluice waterwork was built near the village Nikolaevskaya. If we connect this hydroelectric facility with the project of N. P. Puzyrevsky, its number corresponds to No. 5. The need for its construction was associated with the provision of navigation in the area from the exit from the lower approach channel of sluice No. 15 to the entrance of the Nikolaevsky hydroelectric complex. The current pressure head is 3.8 – 4.0 m. The hydroelectric complex has: shipping lock, fish pass gateway No. 1, fish pass gateway No. 2, complex (“shipping”) dam, spillway dam, earth dam, spawning fish pass channel with a regulation sluice. The complex dam (Poare farms) allows you to adjust the amount of backwater and ensure the passage of high water without backwater of the water level of the Don.

The Konstantinovsky hydroelectric complex (unfinished complex according to the scheme of N. P. Puzyrevsky-No. 4 in the 1910s) was put into operation in 1982 and began to provide navigation on the section of 43 km from the Nikolaevsky hydroelectric complex to the site of the Konstantinovsky hydroelectric complex. The hydroelectric complex has the following: shipping gateway, gateway for high-speed shipping, fish pass gateway No.1, fish pass gateway No. 2, spillway dam with a spillway control, earth dam, spawning fish pass channel with a regulation sluice. The design head at the hydroelectric facility is 3.2 m. The calculation pressure head in the hydroelectric complex is 3.2 m [19].

The section of the Lower Don from the Kochetovsky hydroelectric complex to the mouth is essentially a river in a free state with a modified hydrological regime 45 rifts are separated by short millpond valleys in the segment with a length of 164 km. Despite the large volume of dredging, some of the rifts have retained their typical channel formations – sidewalls, ridges. This section is difficult for navigation due to the limited width of the ship's course and the sharp turns of the channel.

3. Results
The residual resource of hydraulic structures of the Don sluice system allows you to establish a safe period of their operation without restrictions or with restrictions, or to make a decision on the repair or liquidation of hydraulic structures and part of its elements [20]. The main property that determines the resource of the system is the reliability of its elements, i.e. reliability and trouble-free operation during a certain period of operation. The reliability and uptime of the system as a whole are determined from the condition that each element of the system can be in one of two states-operational or failure.

Existing methods [21] of the examination of hydraulic structures aimed at assessing overall fitness of load-bearing structures for further use are applicable to hydraulic structures of the Don sluice system.

The monitoring is carried out taking into account the existing regulatory documents for the design, manufacture and specific use, it also highlights the main requirements to the process of measuring the technical condition of hydraulic structures of the Don sluice system using modern non-destructive testing equipment, namely the development of software and hardware complex for performance monitoring of the technical condition of hydraulic structures, which are intended to define parameters of different defects and damages, as well as calculating the projected life of the residual resource of their elements.

We calculated the finite element models of the complex dam – the Poare farm, which allowed us to calculate the efficiency of hydraulic structures of the Don sluice system in Figures 1-3.
With its help, it is possible to evaluate each defect, as well as the residual resource before the loss of the load-bearing capacity of reinforced concrete elements of hydraulic structures of the Don sluice system. The complex also allows us to assess the influence of a number of factors on the reliability of individual elements of the structure, the most characteristic of which are filtration, abrasion, leaching processes and the degree of wear on the sections with different hydraulic characteristics.

The design and construction of the project “Development and implementation of a complex project of reconstruction of the Azov-Don water basin, stage III (the Bagaevsky hydropower complex)” is conducted in accordance with the Decree of the RF Government dated February 29, 2016 No. 327-r
“Strategy of the development of inland water transport of the Russian Federation for the period up to 2030”. The Bagaevsky hydroelectric complex will be located on 3089 km of the ship's course, near the village Arpachin (according to the scheme of N. P. Puzyrevsky - stock No. 2, the location of which is slightly higher than the projected UPC “Transgidroproekt”) [22].

The Bagaevsky hydroelectric complex is a water transport facility designed to provide guaranteed navigable depths during navigation. The structure of hydraulic structures of the Don sluice system includes: structures designed to raise the water level on the problem section of the river and water passes; ship-passing structures; fish-passing structures that provide favorable conditions for fish passage from one water body to another one. In terms of design and structure of constructions, the Bagaevsky hydroelectric complex largely repeats the one which has operated on the Don River since 1982, the Konstantinovsky hydroelectric complex. The maximum design pressure head at the hydroelectric complex (the difference between the NRL and the minimum downstream level with \( P = 99\% \)) is 3.8 m, on average, the level backwater does not exceed 2.0 m.

In the field of hydraulic engineering, various methods of increasing the minimum depth are widely known. This includes dredging the bottom, removing rapids in certain sections of the riverbed, straightening the riverbed with the help of regulatory structures (longitudinal stream-directing dams, semi-dams and dams, bottom dams, coastal spurs, etc.) and river sluicing. Taking into account the variety of conditions that determine the nature of a particular section of the river, when working out the projects to increase navigable depths, it is necessary to consider several solutions, including the above mentioned methods.

It is really possible to guarantee the dimensions of the shipping route in Russia only by water retention (river sluicing), but the retaining structures during high water should pass water with a minimum difference in water levels in reaches, and these levels should not exceed the common maximum values. Thus, the dam gates must be separable or stacked on a flatbed. We should not reject the possibility of using flexible elements [15] to create a level support, as means of reducing the cost of hydroelectric facilities.

4. Conclusion
The national standard GOST R 22.1.12-2005 allows us to formulate the main requirements for the continuous monitoring of hydraulic structures of the Don sluice system. The State Water Register is maintained in accordance with Article 31 of the Water Code of the Russian Federation, Decree of the Government of the Russian Federation No. 253 of 28.04.2007 “On the Procedure of Maintaining the State Water Register”, “Order of the Ministry of Internal Affairs of the Russian Federation No.186 of 16.07.2007”, “On Approval of Rules of Entering Information into the State Water Register”, “Order of the Ministry of Internal Affairs of the Russian Federation No. 138 of 29.05.2007”, “On Approval of the Form of the State Water Register”. The high-quality monitoring of hydraulic structures allows us to assess the change in the stress-strain state over time under various combinations of loads, in relation to hydraulic structures of the Don sluice system. The analysis of unsatisfactory condition of individual hydraulic structures in the south of Russia indicates the unresolved problems with their operation, insufficient funds allocated for multi-factor assessment of the facts affecting their reliability and safety, the low qualification of the operating personnel.

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