Determination of the optimal modes of filling and emptying the chamber of the navigational lock of a low-pressure hydroelectric complex

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Abstract. The construction of the low-pressure Nizhny Novgorod hydroelectric complex covered by the Strategy for the Development of Inland Water Transport of the Russian Federation for the period up to 2030 envisages a ship lock as part of the hydroelectric system to ensure ships passage. One of the options under consideration is a ship lock with a head power system, which uses short bypass water-circulating culvert for filling and emptying the chamber. At the same time, an important task is to select the optimal modes ensuring movement of the gates of the filling and emptying systems, in which the normative values of the hydrodynamic forces influencing the vessel in the chamber during the lock process would not be exceeded. The article describes the experience of performing laboratory hydraulic studies of the ship lock model and presents the results of determining the optimal modes of locks movement in the ship lock filling and emptying systems. The studies were carried out on a model located in the hydrotechnical laboratory named after Professor V.E. Timonov of the State University of Maritime and River Fleet named after Admiral S.O. Makarov. The article describes the experience of performing laboratory hydraulic studies of the ship lock model and presents the results of determining the optimal modes of gates movement in the ship lock filling and emptying systems. The studies were carried out on a model located in the hydrotechnical laboratory named after Professor V.E. Timonov of the State University of Maritime and River Fleet named after Admiral S.O. Makarov. The studies included three series of measurements taken at different speeds of gates movement. The speeds were assigned based on the following idea: the maximum hydrodynamic forces of one of the series were close to the permissible values, and of the other two – 30–50 % smaller and larger, respectively. The experimental results determined the optimal operating modes of the systems for filling and emptying the lock chamber. It is recommended to select of the optimal modes of gates movement in full-scale conditions on the newly built ship locks immediately after their construction.

1. Introduction
The problem of difficult navigation conditions on the Volga River section between the Nizhny Novgorod and Cheboksary hydroelectric complexes was aggravated due to the decision not to fill the Cheboksary reservoir to the design level made in 1989 [1–3]. Thereafter, for more than 30 years, many researchers have undertaken efforts to formulate proposals (in the absence of funding) that could solve...
the difficult problem of improving navigation conditions in the downstream of the Gorodetsky lock [3, 4]. Proposals to remove restrictions on the difficult navigable section included the installation of a third line of locks; reconstruction of existing navigational passages accompanied by simultaneous dredging works.

As a result, the Strategy for the Development of Inland Water Transport [5] implies the construction of a low-pressure hydroelectric complex as the most cost-effective project not only solving shipping problems but also providing additional communication between the shores for vehicles.

The version of the low-pressure hydroelectric project proposed in [1] includes a blind earth dam, a reinforced concrete spillway with a wide threshold and 16 spillway openings each being 20 m wide, and an earth stream-guiding dam. To ensure navigation, a two-strand lock with a capacity not lower than similar locks of the Volga River has been proposed. The throughput should be ensured by an optimal power system chosen based on the results of hydraulic studies.

The norms for ship locks with heads less than 10 m recommend the use of a head power system, in which water is supplied to the chamber and emptied through devices located in the upper and lower heads of the ship lock. Based on the analysis of existing power systems [6,7], it is possible to distinguish power systems through short bypass culverts [8] used both for filling and emptying the chamber, systems with filling from under flat lifting and lowering gates [9–11], as well as systems with filling through the radial lock drop gates with double curvature cladding and gallery drainage scheme [12]. The efficiency of emptying systems through short bypass culverts is confirmed by the use of such systems in more than 70% of Russian locks. Considerations of economy and unification of the adopted technical solutions lead to the decision to use short bypass culverts in the chamber filling system.

The present work is devoted to the study of power supply systems for a navigational lock with short bypass culverts in laboratory conditions on a physical model in the hydrotechnical laboratory named after Professor V.I. Timonov, Admiral Makarov State University of Maritime and Inland Shipping [13].

2. Materials and Methods

Laboratory studies were carried out on a model of a lock with a chamber with dimensions in the plan of 10 to 1 m and a side height of 0.64 m with the side walls of the chamber made of transparent plexiglass. These dimensions correspond to the chambers of the Volzhsky locks on a scale of 1:30. In addition to the lock chamber, the experimental facility shown in Fig. 1 included upstream and downstream tanks equipped with water level regulators, which made it possible to set the required water marks in the ponds. The lock chamber is separated from the reservoir tanks by heads of the same design with short bypass culverts with working gates. Maneuvering of the gates was carried out using an electric drive controlled from the general control panel of the stand. The navigational gate of the lock on the model is deaf and it imitates the configuration of the corresponding structures in nature. The model of the vessel “Volgo-Don” (project 1565) made on a scale of 1:30 was installed at the upper head behind the resting area.

The laboratory experimental setup was equipped with measuring and control equipment necessary to carry out research. A precision inclinometer ZeroTronic with an error in measuring the vertical angle of no more than 10 seconds was installed on the ship model. The position of the open water surface in the ponds and the chamber was monitored using four ultrasonic water level sensors located in the upper and lower ponds, at the bow and stern of the vessel. The sensors determined the position of the free surface with an accuracy of ±1 mm, the data on the water level were displayed on the stand control panel. Each experiment was preceded by calibration of measuring instruments, which implied determining the relationship between the measured physical quantity in a given range and the digital

1 SP 101.13330.2012 Retaining walls, shipping locks, fish passages and fish protection structures. Date of introduction January 1, 2013
value of the signal coming from the analog-to-digital converter. The laboratory’s water circulation system provided the model of the lock with a water flow rate of up to 100 l/s, which at a scale of 1:30 corresponds to a full-scale value of up to 500 m³/s.

Figure 1. Schematic of the experimental facility
(The dimensions are indicated for the model in cm (in brackets - for nature in m))

The self-similarity of hydraulic modes in the experimental setup [14] was controlled by Reynolds numbers, which were at least 3,000–5,000 even at pressures close to zero values.

As is known [15], the only similarity criterion for hydraulic modeling of flows with an open surface in the region of self-similarity is the Froude number. The uniformity of this criterion for the model and nature ensures the similarity of hydraulic processes without fluid replacement. Then, with the accepted linear scale \( a = 30 \), the recalculation of the data obtained on the model for a full-scale object is performed using the following scale factors:

- for the slope of the open water surface: \( a_i = 1.00 \);
- for speed: \( a_\nu = \sqrt{a} = 5.48 \);
- for time: \( a_t = \sqrt{a} = 5.48 \);
- for water consumption: \( a_Q = a^{5/2} = 4929.50 \);
- for longitudinal hydrodynamic force: \( a_P = a^3 = 27000 \).

The permissible value of the longitudinal force was calculated in accordance with SP 101.13330.2012\(^2\) according to the formula:

\[
P_{add} = 1.4\sqrt{W} = 57.82 \text{ kN};
\]

where \( W \) is displacement of the vessel, t.

The task of the research was to determine the optimal speeds of gates movement on the filling and emptying systems, at which, the values of the hydrodynamic forces influencing the vessel in the

\(^2\) SP 101.13330.2012 Retaining walls, shipping locks, fish passages and fish protection structures. Date of introduction: January 1, 2013
The tests were carried out in three series, in each of which at least three experiments were performed. Experiments that did not provide the required homogeneity of the data series according to Student were discarded [16].

The series of experiments differed from each other in the speed of the working gates movement, which were assigned in such a way that the maximum hydrodynamic forces influencing the ship during the locking process in one of the series were close to the permissible value, and in the other two they turned out to be respectively smaller and larger by 30–50%.

The magnitude of the hydrodynamic force was determined from the values of the longitudinal trim of the vessel, obtained using the inclinometer, multiplied by its displacement. The hydraulic characteristics of the sluice, such as the change in the water level in the chamber, the flow rate of water in the sluice through the culverts and their flow coefficient, were determined according to the classical method [17].

3. Results
As a result of the research, the hydraulic characteristics of filling and emptying the lock chamber were obtained at various speeds of the valves. Based on the data obtained, the relationships between the maximum (peak) values of the hydrodynamic forces and the speed of gates movement were built. Such dependences enabled to obtain the optimal speeds of the gate movement corresponding to the filling and emptying processes using the permissible value of the hydrodynamic force. The experiment results determined the optimal movement modes of the gates being 0.79 m/min when filling and 1.64 m/min when emptying; such speeds provided the standard parking conditions for the design vessel of the “Volgo-Don” type. The criterion for evaluating the results obtained was, on the one hand, the prevention of the longitudinal hydrodynamic force exceeding the permissible value, on the other hand, the presence of a minimum reserve of this value.

Graphs describing the process of lifting the gates at their optimal speed are shown in Fig. 2.

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![Graph](image)

**Figure 2.** Changing the gates lifting height when driving at optimal speeds

As can be seen from Fig. 5, the maximum value of the hydrodynamic force during filling was 57.79 kN, and during emptying – 57.32 kN with the maximum permissible value of 57.82 kN.
Figure 3. Changing water level in chamber

Figure 4. Change in consumption

Figure 5. Change in hydrodynamic force influencing the ship

4. Discussion
Calculations show that the lock chamber is filled in the optimal mode during 629 s and is emptied during 523 s, which correlates with the actual data [17] of structures in use today on the waterways of Russia and the world. At the same time, the results obtained can be corrected towards locking acceleration by introducing multi-speed modes of gates movement, which can also be differentiated depending on the displacement of ships.

These modes are selected in the best way under the conditions of an already built structure and in the general case involve a series of experiments to study the conditions of the ship’s anchorage at different speeds of gate movement. Such studies together with the measurement of the longitudinal trim of the vessel also assume the simultaneous fixation of forces in the mooring ties and water levels at several points of the chamber. For these purposes, such measuring instruments as submersible pressure sensors, electronic dynamometers and inclinometers can be used.
A patented device developed by specialists of the testing center of hydraulic structures headed by Ryabov G.G. can be used as a device for measuring the longitudinal trim of a ship [18]. Such a device has a number of significant advantages in comparison with its counterparts and they are as follows: compactness, waterproof design, high measurement accuracy (error no more than 0.1°), the possibility of wireless data transmission including the one to mobile devices.

It is advisable to carry out a complex of field studies to select the optimal modes of gate movement immediately after the facility construction during the commissioning phase. Such a complex should include not only the study of the vessel’s anchorage conditions in the lock chamber but also the determination of the effects on the vessels awaiting lock at the berths in the approach channels. As a result of such works, modes leading to significant savings in lock time of up to 20–30 % can be determined.

5. Conclusions
In the course of laboratory hydraulic studies on the model of the lock, the optimal modes of gates movement were determined, the speed for filling was 0.79 m/min and for emptying – 1.64 m/min. Such speeds of gates movement provide the standard conditions for anchorage in the lock chamber in the process of locking the design vessel of the “Volgo-Don” type.

The research results can serve as a basis for pre-design studies of similar structures.

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