Throughput of the water of shutter with flexible working bodies

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Abstract. The author together with Bochkarev V developed a hydraulic automatic water level controller with flexible working bodies. To determine the throughput and determine the optimal profile shape of the weir of its shutter, experimental studies were conducted. They were carried out by the method of physical modeling of the model and nature in an experimental setup, with the study of three types of shutter models with flexible working bodies with the shapes of a part of the spillway in the form of a board, non-vacuum and elliptical vacuum profile. Based on the results of these studies, without and with a side stream, formulas and dependency curves are obtained for determining the flow rates of the spillway with three forms of its part of the spillway. An analysis of the results of the study showed that the shutter with the spillway non-vacuum profile without has a slightly lower throughput than others, but is characterized by stable operation without vibration and is therefore recommended for use.

1. Introduction

Current trends and the scale of development of hydraulic engineering and land reclamation raise the problem of effective control of the water level in irrigation systems. To maintain the required water level in the channel in front of the shutter of the partition structure and to supply a predetermined constant flow of water to the branches, the automation of the hydraulic engineering partition structures is performed.

Due to the widespread use of shutters on partition walls of irrigation systems and their remote location from power lines, hydraulic shutters-automatic machines are most effective. They work on the use of hydraulic energy from a moving jet of water. The most widely used of them are the designs developed and described in the works of SH.S. Bobokhidze [1], Ya.V. Botchkarev [2, 3, 4], N.A. Zakusilov [5], O.G. Zatvornitsky [6], P.I. Kovalenko [7], E.E. Makovsky [8]. The main thing in these designs is a metal shutter (flat, segment, sector) of one or another design, the requirement for them to significant changes in water level, preventing overflow of water through the top of the shutter, the need periodic mechanical cleaning of floating bodies and debris in the space in front of the shutter, the need for capital facilities. This, of course, is expensive and prevents their widespread adoption in production. Today, with the advent of soft rubberized (reclamation) fabrics, combined soft (flexible) designs of hydraulic automatic blinds have appeared. They combine the properties of soft (flexible) materials with traditional hard materials. They are described in the works of M.-G.A. Kadirova [9], I.A. Petrov [10], B.I. Sergeev [11], B.I. Sergeev, P.M. Stepanov, V.V. Shumakov [12, 13]. However, in these designs, the main drawback is either the inability to wash part of the channel before the shutter from deposits or the need for periodic mechanical cleaning of floating bodies and debris in the...
space in front of the shutter. The designs of these shutters are cheap, light, environmentally friendly, maintainable, economical, and, if necessary, can be mobile, portable, and prefabricated, they are non-metal-consuming. To eliminate the aforementioned drawbacks of these automatic ones, to shutter-automatic, a constant water level in the part of the channel in front of the shutter, automatically skipping floating bodies and removing deposits from the channel in front of the shutter, we, together with professor Ya.V. Botchkarev proposed a water level autoregulator [14]. It combines the properties of soft (flexible) materials with traditional hard materials. An integral part of this water level autoregulator is a shutter with flexible working elements, consisting of a tank formed by a board and a soft cloth. To determine the flow rate of water passing through the water level autoregulator [14] downstream from the partition structure, and thus determine the possible amount of water for consumers in the lower channel, it is necessary to know its throughput. To determine the throughput of a water-containing shutter with flexible working bodies of a water level autoregulator [14], to ensure its stable vibration-free operation, as well as the optimal shape of its spillway profile, experimental studies were carried out.

2. Materials and methods
The studies were carried out by the method of physical modeling, using the criterion of geometric similarity of the model and nature. The modeling of the studied phenomena was carried out according to the criteria of the gravitational similarity of Froude and the dynamic similarity of forces. The scale of the models about nature was adopted 1: 4.

The experimental setup consisted of a tray 10 m long, 1.0...0.5 m high, 0.378 m wide. The maximum flow rate of water supplied to the tray was 0.0561 m$^3$/s. The tray had a closed water supply system, which was supplied using a pump.

When studying the throughput of a water-containing shutter with flexible working bodies, we studied 3 models of this shutter with a spillway profile:

a) in the form of a flat board made of transparent organic glass with a thickness of 0.006 m, figure 1a;

b) in the form without a vacuum profile constructed according to the Krieger – Ofitserov coordinates [15, 16], figure 1b.

c) in the form of a vacuum profile of an elliptical shape constructed according to the coordinates of N.P. Rozanov [16, 17, 18], figure 1v.

Each of the models consists of the rigid part of the spillway (1) of the profile: a - in the form of a flat board made of transparent organic glass, b - in the form without a vacuum profile constructed according to the coordinates of Krieger-Ofitserovs c) in the form of a vacuum profile of an elliptical contour constructed according to the coordinates N.P. Rozanov, covered with elastic material from ameliorative rubberized fabric. The front part (2) and side parts (3) of the model are made of elastic
material (reclamation rubberized fabric). The rigid part of the spillway (1), the front part (2), and the side parts (3) of the shutter model, together with the rigid box of the bottom part of the shutter (4), form a single shutter capacity. The rigid box (4) located at the bottom of the shutter is made of organic glass, has a width of 0.378 m, a length of 0.54 m, a height of 0.04 m, and is attached to the bottom of the tray. The dimensions of the model elements were determined as follows: \( L_{\text{ob}} = 0.38 \, \text{m} \), where \( L_{\text{ob}} \) is the length of the soft shell, \( L_x = 0.38 \, \text{m} \), where \( L_x \) is the length of the chord of the spillway shutter model, \( L_{\text{kor}} = 0.54 \, \text{m} \), where \( L_{\text{kor}} \) is the length of the lower part (case) of the shutter model, \([\alpha]_{\text{max}} = 0.611 \, \text{radians}, \) where \([\alpha]_{\text{max}} \) is the maximum chord angle of the spillway part of the shutter relative to the horizontal.

The filling of the water-carrying shutter was carried out from a pipe with a diameter of 0.025 m, adjacent to the shutter box through the side wall of the tray and supplying water from the tank of the float switch of the upstream level. An air outlet with a diameter of 0.006 m was made to remove air during the period of filling the shutter tank with water in the upper part of the spillway of the shutter models.

The shutter was emptied through the outlet-drain hole with a diameter of 0.016 m, located in the shutter body from the rear side. The regulation of the water level in the upper part of the channel in front of the shutter was carried out using a float switch for the upper water level at various rates supplied to the tray. The float switch for the water level in the upper part of the tray in front of the shutter was a container made with a base size of 0.1 m×0.1 m made of organic glass in the form of a rectangular prism. It was installed near the side of the tray wall. Its capacity was in communication with the upper part of the tray in front of the shutter with a pipe with a diameter of 0.04 m, the inlet of which was located 1.5 meters from the beginning of the location of the water-containing shutter in the direction of the upper part of the tray. The level sensor had a float. It was mounted at a predetermined level in the upper part of the tray in front of the shutter. It was made of polystyrene and was firmly fixed on a vertical centered rod. A valve was installed at the lower end of this rod. When changing the position of the float, it partially or completely blocked the hole of the pipe with a diameter of 0.025 m, the communicating capacity of the float with the capacity of the water-containing shutter. Modeling of elastic material (soft shell), rubberized reclamation fabric was carried out according to the maximum specific tension. This issue was considered in the works of A.P. Nazarov [19, 20].

Most of the experiments were carried out with a sequential increase in costs. Measurements of all parameters were carried out 15...20 minutes after changing the flow rate or any of the values. During this time, a constant flow mode was set in the tray. In general, the flow coefficient is the following function (1)

\[
m = f(H, h_0/H, [\alpha], [\alpha]_{\text{max}}, h_{\text{vac}}/H, [\sigma]_n, Fr, We, Re)
\]

where \( H \) is the depth of water in the channel (tray) in front of the shutter, \( h_0 \) is the height above the top of the shutter spillway taking into account the speed pressure, \( H_r \) is the height of the shutter rise relative to the bottom of the channel (tray), \([\alpha] \) is the angle formed by the chord of the shutter spillway or shield with the horizontal, \([\alpha]_{\text{max}} \) is the maximum angle formed by the chord of the shutter spillway or shield with the horizontal, \( h_{\text{vac}} \) is the vacuum pressure under the stream on the part of the spillway of the shutter, \([\sigma]_n \) is the coefficient taking into account the flooding of part of the spillway of with water behind the shutter, \( Fr \) is the Froude number, \( We \) is the Weber number, \( Re \) is the Reynolds number.

It is practically impossible to take into account the influence of all these parameters on the change in the flow coefficient. The calculation of the throughput of the shutter model in the absence of lateral outflows was carried out according to the well-known formula (2)

\[
Q_t = m^* b^* \sqrt{2^* g^* h_0^* \sqrt{h_0}}
\]

(2)
From formula (2) in the absence of lateral outflow through the model gate for each fixed angle that is formed by the chord part of the spillway or a flat board with a horizontal, the flow coefficient is determined by the formula (3)

$$m = Q_i / \left( b \sqrt{2 g h_0} \right)$$  \hspace{0.5cm} (3)

The lateral outflow flow rate through the model gate for each fixed angle, which is formed by the chord part of the spillway or a flat board with a horizontal plane, is determined by the formula (4)

$$Q_z = Q_i - Q_1$$  \hspace{0.5cm} (4)

where $Q_i$ is the total flow going through the tray.

3. Results and discussion
The throughput of a water-containing shutter with flexible working bodies with a part of the spillway in the form of a flat board was investigated in detail by V.N. Schedrin [21]. He derived an empirical dependence for determining the flow coefficient depending on the angle of elevation of a flat board $[\alpha]$ relative to the horizontal plane $m = f (\alpha)$ without taking into account lateral outflows. According to him [21], this flow coefficient varies within $m = 0.326...0.514$.

The mathematical processing of the data of our studies of a water-containing shutter with flexible working bodies with a part of the spillway in the form of a flat shield in the absence of lateral outflows showed that the flow coefficient $m$ depending on the $h/H_z$ ratio varies in a parabolic dependence, figure 2.

$$m = 3.718 \left( h / H_z \right)^2 - 3.371 \left( h / H_z \right) + 1.095$$  \hspace{0.5cm} (5)

With $h/H_z = 0.19...0.5$, the flow coefficient varies within $m = 0.33...0.52$. In general, this is consistent with the data of V.N. Schedrin [21].

![Graphs](image)

**Figure 2.** Graphs of dependence $m = f_1(h/H_z)$; $m_p = f_2(h/H_z)$; $Q_{b,i}/Q_i = f_3(h/H_z)$, obtained for a water-containing shutter with flexible working bodies with a part of the weir in the form of a flat board.

As a result of mathematical processing of our results of studies of a water-containing shutter, with flexible working bodies and a spillway profile in the form of a flat board with lateral outflows, we
obtained a cubic parabolic dependence of the reduced flow coefficient \( m_p \) depending on the ratio \( h/H_z \) (figure 2).

\[
m_p = 50.65*(h / H_z)^3 + 55.567*(h / H_z)^2 - 20.67*(h / H_z) + 3.042 \tag{6}
\]

At \( h/H_z = 0.20...0.45 \), the reduced flow coefficient varies within \( m_p = 0.375...0.725 \).

And also a quadratic parabolic dependence of the ratio of the flow rate of the lateral outflows \( Q_{b.i} \) to the total flow rate \( Q_i \) going through the tray.

\[
Q_{b.i} / Q_i = 2.668*(h / H_z)^2 - 2.822*(h / H_z) + 0.711 \tag{7}
\]

With \( h/H_z = 0.18...0.5 \); \( Q_{b.i}/Q_i = 0.04...0.28 \); that is, \( Q_{b.i} = (0.04...0.28) \times Q_i \)

The results of the study of a model of a water-containing shutter with flexible working bodies and part of the spillway in the form without a vacuum profile at \( H_p = 0.15 \) m showed: in the absence of lateral outflows and a fixed angle of elevation of the chord of a part of the spillway of the shutter \([\alpha]\), the flow coefficient \( m \) varies depending on the ratio \( h/H_z \) according to the following parabolic dependence, figure 3.

\[
m = -0.994*(h / H_z)^2 - 2*5964*(h / H_z) + 0.3505 \tag{8}
\]

At \( h/H_z = 0.05...0.45 \); the flow coefficient varies within \( m = 0.37...0.45 \).

If there are lateral outflows through a water-containing shutter with flexible working bodies and part of the shutter spillway in the form without a vacuum profile, when the gap between the sidewalls of the tray and the side of the shutter is 0.0035 m, the flow coefficient \( m_p \) varies depending on the \( h/H_z \) ratio next cubic parabolic dependence.

\[
m_p = -28.07*(h / H_z)^3 + 25.263*(h / H_z)^2 - 7.579\cdot(h / H_z) + 1.2579 \tag{9}
\]
At $h/H_z = 0.075...0.45$, the flow coefficient varies within $m = 0.775...0.45$. And also, as a result of the studies, a quadratic parabolic dependence of the ratio of the lateral flow rate $Q_{b,i}$ to the total flow rate $Q_i$ going through the tray was obtained.

$$Q_{b,i} / Q_i = 3.5242*(h / H_z)^2 - 2.8193*(h / H_z) + 0.6438$$ \hspace{1cm} (10)$$

At $h/H_z = 0.08...0.40; Q_{b,i}/Q_i = 0.1...0.5$; that is, $Q_{b,i} = (0.1...0.5) \cdot Q_i$

Studies of the throughput of a water-containing shutter with flexible working bodies with a part of the spillway of the vacuum profile of an elliptical outline ($b/a = 2$) showed that in the absence of lateral outflows and a fixed angle of elevation [alpha] of the spillway part of the shutter, the flow coefficient $m$ varies depending on the ratio $h/H_z$ according to the following parabolic dependence, figure 4.

$$m = -1.8348*(h / H_z)^2 + 1.009*(h / H_z) + 0.4512$$ \hspace{1cm} (11)$$

At $h/H_z = 0.04...0.4$ the flow coefficient varies within $m = 0.44...0.577$, which is consistent with the data of N.P. Rozanov [17, 18].

If there are lateral outflows through a water-containing shutter with flexible working bodies and part of the spillway of the vacuum profile of an elliptical shape ($b/a = 2$), when the gap between the sidewalls of the tray and the side face of the shutter is 0.0035 m, the flow coefficient $m_p$ changes to depending on the ratio $h/H_z$ according to the cubic parabolic dependence.

$$m_p = -20.8724*(h / H_z)^3 + 17.2197*(h / H_z)^2 - 4.7353*(h / H_z) + 1.059$$ \hspace{1cm} (12)$$

At $h/H_z = 0.075...0.375$ the flow coefficient varies within $m_p = 0.75...0.595$. And also as a result of the studies, a quadratic parabolic dependence of the ratio of the lateral flow rate $Q_{b,i}$ to the total flow rate $Q_i$ going through the tray was obtained

$$Q_{b,i} / Q_i = 4.5357*(h / H_z)^2 - 3.1750*(h / H_z) + 0.6056$$ \hspace{1cm} (13)$$

At $h/H_z = 0.04...0.29; Q_{b,i}/Q_i = 0.05...0.39$; that is, $Q_{b,i} = (0.05...0.39) \cdot Q_i$

![Figure 4](image-url). Graphs of dependence $m = f_1(h/H_z); m_p = f_2(h/H_z); Q_{b,i}/Q_i = f_3(h/H_z)$ obtained for a water-containing shutter with flexible working bodies with a part of the spillway in the form of a vacuum profile of an elliptical shape ($b/a = 2$).
Studies of a water-containing shutter with flexible working bodies with three forms of a part of the spillway showed that the water-containing shutter with flexible working bodies and the vacuum profile of the part of the spillway of an elliptical outline has the highest throughput, taking into account lateral outflows, \((b/a = 2)\), \(m_p = 0.75\ldots0.595\). The shutter with a part of the spillway in the form of a flat board has a lower throughput, \(m_p = 0.725\ldots0.375\), and the shutter with a part of the spillway non-vacuum profile, \(m_p = 0.715\ldots0.45\), has even less low throughput. However, as visual observations have shown, a water-containing shutter with flexible working bodies and a vacuum profile of a part of the spillway of an elliptical shape \((b/a = 2)\) and a water-containing shutter with a part of the spillway in the form of a flat board during operation are characterized by vibration, unstable operation. This suggests the appearance of reduced pressure under the stream on the crest of a part of the weir of these shutters, as in dams with a vacuum profile, the outline of the weir part on the crest \([17, 18]\).

4. Conclusion

1. The formulas obtained as a result of studies for determining flow coefficients with-out taking into account lateral outflows and flow coefficients taking into account lateral outflows allow determining the throughput of water-containing gates with flexible working bodies, with the shapes of part of the spillway in the form of a) a flat board, b) without a vacuum profile and v) the vacuum profile of an elliptical shape.

2. The research results showed that a water-containing shutter with flexible working bodies and a part of the spillway in the form of a vacuum profile has a higher throughput and a slightly smaller water-containing shutter with a part of the spillway in the form of a flat board and an even smaller water-containing shutter with a part of the spillway in the form without non-vacuum profile.

3. A water-containing shutter with flexible working bodies and a spillway in the form of a vacuum profile and a water-containing shutter with flexible working bodies and a spillway in the form of a flat board at angles of elevation of the plane the board or part of the spillway relative to the horizontal plane is more than 0.349 radians are characterized by vibration. The water-containing shutter with a part of the spillway in the form without a vacuum profile has stable operation without vibration. Therefore, for practical use, it is recommended to use a water-containing shutter with a part of the spillway in the form without a vacuum profile.

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