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RESEARCH OF HYDRODYNAMIC PRESSURE AND THROUGHPUT OF A WATER-CONTAINING SHUTTER WITH FLEXIBLE WORKING BODIES WITH VARIOUS SHAPES OF ITS SPILLWAY PART

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The article describes an experimental setup, models, test procedure and results of experimental studies of hydrodynamic pressure and throughput of a water-containing shutter with flexible working bodies with three shapes of its spillway part: in the form of a board, non-vacuum and vacuum profiles.

Keywords: vibration; flow coefficient; generalized flow coefficient; lateral outflows; spillway part profile shape; board; vacuum; non-vacuum.

Modern trends and the development scale of hydraulic engineering and land reclamation put forward the problem of effective managing over the water level in the irrigation system as one of the most important. To maintain the required water level in the upper pool of the partitioning structures and to supply the required water flow to the outlets for economical water consumption, consumers, as a rule, need automation of the partitioning structures. In view of the widespread use of shutters on the partitioning structures of irrigation systems and their remote location from power lines, their hydraulic automation is the most rational from the point of view of economic efficiency. For this purpose, automatic hydraulic shutters are often used, since they operate on renewable hydraulic energy of a moving water stream.

On the partitioning structures of irrigation channels, designs developed and described in the studies of Sh. S. Bobokhidze [1], Ya. V. Bochkarev [2 – 4], N. A. Zakusilov [5], O. G. Zatvornitskii [6], P. I. Kovalenko [7], E. E. Makovskii [8], et al. are being used. The main part in these designs is a metal shutter (flat, segment, valve, sector). The shutter should meet the requirements of a significant water level difference, prevention of water flow over the shutter top, periodic mechanical cleaning of the space in front of the shutter from the drift and debris, and the arrangement of capital structures. These measures are expensive, which hinders their widespread introduction into production.

With the introduction of soft rubberized (reclamation) fabrics, combined soft (flexible) designs of automatic hydraulic shutters have appeared. These shutters, described in the studies of M.-G. A. Kadirova [9], I. A. Petrov [10], V. N. Shchedrin [11], B. I. Sergeev [12], P. M. Stepanov, B. B. Shumakov, and B. I. Sergeev [13, 14], combining the properties of flexible (rubberized) materials (fabrics) and traditional rigid materials, have great application prospects. The designs of these shutters are cheap, economical, non-metal-intensive, lightweight, environmentally friendly, suitable for repair, and, if necessary, can be mobile, portable and dismountable. However, flexible structures also have disadvantages, the main of which are the impossibility of washing the upper pool from sediments and the need for periodic mechanical cleaning of the space in front of the shutter from drift and debris.

To eliminate these shortcomings of automatic shutters with automatic maintenance of the required water level in the upper pool of the structure, automatic passage of floating bodies and washing of sediments from the upper pool of the structure to the lower pool, the author together with Professor Ya. V. Bochkarev has proposed a hydraulic automatic water level controller [15]. This automatic controller combines the properties of flexible and traditional rigid materials. An integral part of such an automatic water level controller is the main shutter with flexible working bodies, consisting of a tank formed by a rigid spillway board and a soft fabric.

However, studies have shown that this main shutter at certain elevation angles of the rigid board with respect to the horizontal axis is characterized by vibration and unstable operation. The reason for this is the low hydrodynamic pressure acting on the spillway part of this shutter with flexible working bodies. This hydrodynamic pressure was studied in detail by V. N. Shchedrin [11]. He has constructed diagrams of the hydrodynamic pressure acting on a similar shutter, consisting of a soft shell and a spillway rigid board, at various elevation

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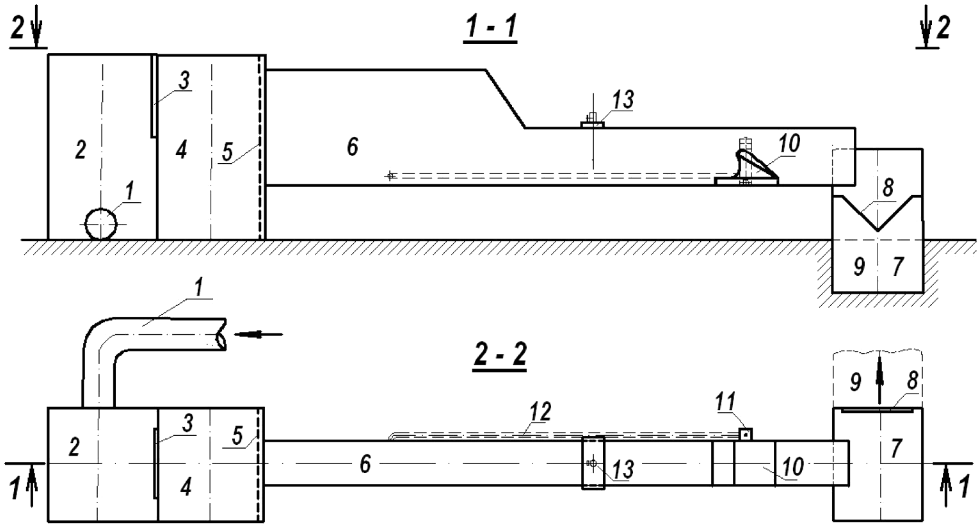

Fig. 1. Experimental setup: *1*, pipe supplying water from the pump; *2*, stilling tank No. 1; *3*, measuring triangular spillway with a thin wall; *4*, stilling tank No. 2; *5*, absorber of the water stream energy in the form of a lattice; *6*, flume; *7*, stilling tank No. 3; *8*, measuring triangular spillway with a thin wall; *9*, spillway trench; *10*, investigated model; *11*, water level controller; *12*, pipe connecting the water level controller with the upper pool of the model; *13*, a mobile shelf with a point-gauge installed on it.

angles of the spillway rigid board. As studies by V. N. Shchedrin have shown, the shape of the diagram of the averaged hydrodynamic pressure acting on the spillway board has a wave-like form. On the crest of the spillway and at small elevation angles of the board, vacuum is formed somewhat below it, which is explained by the desire of the jet to separate from the board; then, there is a jet impact on the board, a pressure surge, then the jet hits again and the pressure increases. Therefore, the pressure diagram on the board has a wave-like form. The vacuum zone, according to the studies of V. N. Shchedrin, extends to 1/2, and with an increase in specific flow rates, this zone descends to 2/3 of the board plane. The upper boundary of the vacuum zone is located on the spillway crest and does not pass to the shell at small angles between the fabric and the board. The lower boundary of the vacuum zone is located on the spillway board. The reasons for the appearance of a vacuum on the spillway board are also described in the studies of N. P. Rozanov [16], B. I. Sergeev, A. P. Nazarov [17, 18]. At that, it should be noted that with an increase in flow rates, there is an increase in pressure fluctuations on the spillway crest. These fluctuations at the Reynolds number $Re = 9.5 \times 10^5$ reach 50 – 60 mm, which leads to vibration and swinging of the shutter and its unstable operation.

In order to ensure stable vibration-free operation of the main shutter of the automatic water level controller with flexible working bodies [1] in the entire range of elevation angles of its spillway part, let us set the task of choosing such a profile of its spillway part, at which this shutter will operate stably and without vibration. In order to do that, it is necessary to choose such a profile of the spillway part, at which the hydrodynamic pressure along the entire contour of the spillway part of the main shutter at all elevation angles of its spillway part will be positive.

This shape of the profile was assumed to be the shape of the spillway part profile in the form of a non-vacuum spillway profile constructed according to the Krieger – Ofitserov coordinates [19, 20]. To prove this hypothesis, as well as to determine the throughput capacity of a water-containing shutter with a spillway in the form of a non-vacuum profile, necessary to calculate its throughput capacity and compare it with the throughput capacity of a water-containing shutter with a spillway in the form of a rigid board, experimental studies have been carried out. The objective of this research was to determine the hydrodynamic pressure acting on the main shutter with the shape of its spillway in the form of a non-vacuum profile and to compare it with the hydrodynamic pressure acting on the main shutter with the shape of its spillway in the form of a rigid board. Based on these studies, it is possible to determine such a profile shape of its spillway part, which will ensure its stable operation. Besides, the task was set to determine the throughput capacity of the main shutter of the automatic water level controller with flexible working bodies [1] with its spillway part in the form of a rigid board and in the form of a non-vacuum profile.

The experimental setup (Fig. 1) consisted of a flume 10 m long, 1.0 – 0.5 m high, and 0.378 m wide. The maximum flow rate of water supplied to the flume was 0.0561 m^3/sec. The flow rate was measured using a triangular measuring spillway with a thin wall. The flume had a closed water supply system, while the water was supplied by a pump.

The studies were carried out by the method of physical simulation, using the criterion of geometric similarity of the model and nature at Reynolds numbers Re = 7145 –

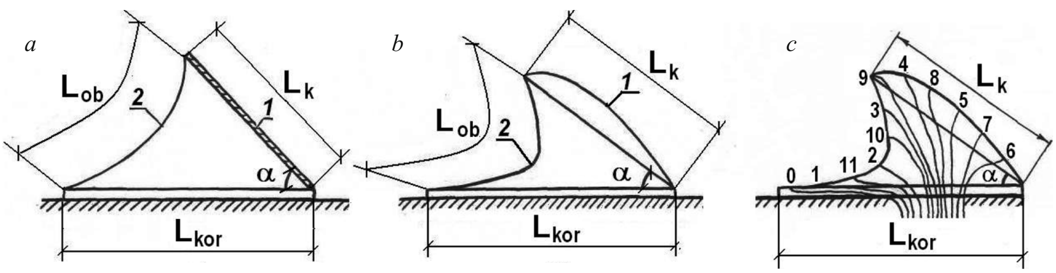

Fig. 2. Models of a water-containing shutter: *a*, with a spillway part in the form of a rigid board; *b*, with a spillway part in the form of a non-vacuum profile; *c*, location diagram of piezometers connection points (points are shown by numbers) to determine the hydrodynamic pressure acting on the units of the model under study; *1*, spillway part; *2*, shell.

56,202 > Re_{cr} = 300, which corresponds to the quadratic resistance area for open channels [21], and the Froude numbers Fr = 0.51 – 10.5 with self-similarity of the considered phenomena.

Simulation of the studied phenomena was carried out according to the criteria of Froude's gravitational similarity, dynamic similarity of forces, similarity criteria of dynamic processes under the action of elastic forces (Cauchy's criterion). Simulation of an elastic material was carried out according to the maximum linear tension according to the recommendations of A. P. Nazarov [17, 18]. Based on it, one can determine the dependence for the linear transverse tension

$$T = K_1 \rho g L^2. \quad (1)$$

For the model and nature, the similarity criterion is obtained in the form

$$T/EL = \text{idem}. \quad (2)$$

The similarity scale of elastic moduli of an elastic material

$$\lambda_E = \lambda_T/\lambda_L, \quad (3)$$

or taking into account Eq. (1)

$$\lambda_E = \lambda_L. \quad (4)$$

The similarity scale of the Poisson's ratios of an elastic material should be $\lambda_M = 1$.

Thus, the tension similarity scale will be equal to the square of the linear scale, and the elastic modulus scale will be equal to the linear scale:

$$\lambda_T = \lambda L^2. \quad (5)$$

The scale of models in relation to nature was taken as 1:4.

When studying the throughput capacity of a water-containing shutter with flexible working bodies, two models with the profile shape of the spillway part were investigated:

(a) in the form of a rigid board made of transparent organic glass with a thickness of 0.006 m (Fig. 2*a*);

(b) in the form of a non-vacuum profile constructed according to the Krieger – Ofitserov coordinates [19] (Fig. 2*b*).

Each of the models consisted of a rigid frame spillway part *1* of the profile indicated in (a) and (b), covered with an elastic material made of rubberized (reclamation) fabric *2*, passing into the pressure and lateral parts of the model, forming a single whole with it, and attached to an apron made of organic glass in the form of a box 0.378 m wide, 0.54 m long, 0.04 m high, installed at the bottom of the flume. The dimensions of the model units were taken as follows: L_{ob} = = 0.38 m, where L_{ob} is the shell length; L_k = 0.38 m, where L_k is the length of the board or the chord of the shutter spillway part; L_{box} = 0.54 m, where L_{box} is the length of the shutter box; α_{max} = 0.785 rad, where α_{max} is the maximum elevation angle of the board or the chord of the spillway of the shutter model.

Filling of the water-containing shutter was carried out from a pipe with a diameter of 0.025 m, adjoining the shutter box through the flume lateral wall and supplying water from the tank of the float upper pool level adjuster. To remove air during the filling of the shutter with water, an air outlet hole with a diameter of 0.006 m was made in the upper part of the spillway of each of the shutter models. The shutter was emptied through the outlet spillway hole with a diameter of 0.016 m, located in the shutter box from the lower pool side. The control of water levels in the upper pool of the water-containing shutter was carried out with the help of a float level adjuster in the upper pool at various water flow rates supplied to the flume.

The float level adjuster for the upper pool was a container made of organic glass in the form of a rectangular prism with a base size of 0.1 × 0.1 m, installed behind the flume lateral wall. The adjuster container was connected with the upper pool of the flume by a pipe with a diameter of 0.04 m, the inlet of which was located at a distance of 1.5 m from the end of the water-containing shutter towards the upper pool. The level adjuster float was made of foam and mounted on a vertical centred rod, at the lower end of which a conical valve was installed. At a set level in the upper pool, this valve could partially or completely close the opening of

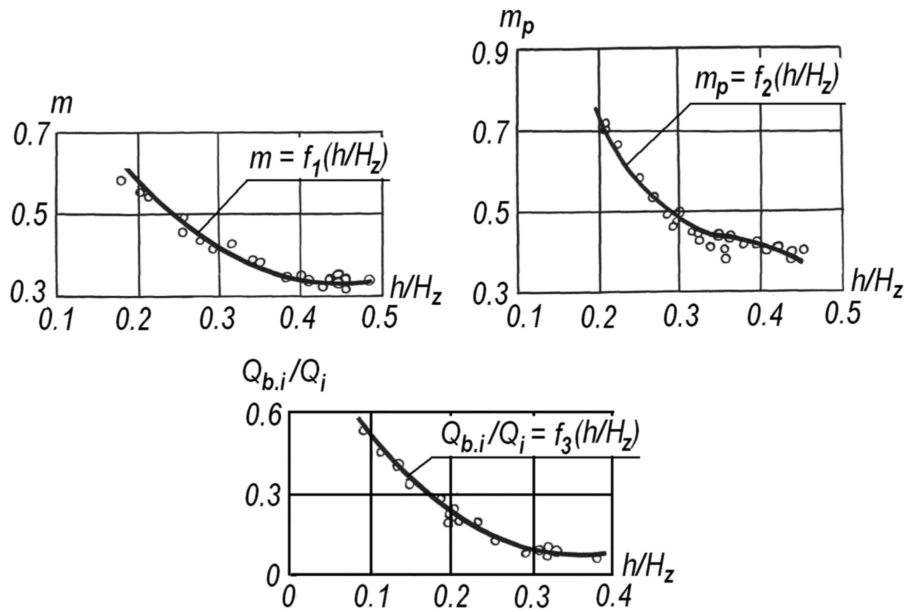

Fig. 3. Graphs of dependence $m = f_1(h/H_z)$, $m_p = f_2(h/H_z)$, $Q_{b.i}/Q_i = f_3(h/H_z)$ obtained for a water-containing shutter with flexible working bodies and a spillway in the form of a rigid board.

a pipe with a diameter of 0.025 m, communicating with the water-containing shutter container. This choice was explained by the highest efficiency of such model during preliminary studies.

Simulation of an elastic material was carried out according to the maximum linear tension. This issue is considered in the studies of A. P. Nazarov [17, 18].

The hydrodynamic pressure acting on a water-containing shutter with flexible working bodies with a spillway part profile in the form of a rigid board was studied in detail by V. N. Shchedrin [11]. He constructed diagrams of the hydrodynamic pressure on this water-containing shutter at various elevation angles of the shutter spillway part α. The studies have shown that at large elevation angles of the spillway board of the water-containing shutter, a reduced pressure is formed on the shutter crest. When studying the hydrodynamic pressure of water acting on a water-containing shutter with flexible working bodies, a model of a water-containing shutter with the shape of a rigid spillway part of a non-vacuum profile was studied (Fig. 2*c*).

The calculation of the throughput capacity of the models in the absence of lateral outflows was carried out according to the formula

$$Q_1 = mb\sqrt{2}gh_0\sqrt{h_0}. \quad (6)$$

In the absence of lateral outflows for each fixed angle, the flow coefficient was determined from the formula

$$m = \frac{Q_1}{b\sqrt{2}gh_0\sqrt{h_0}}. \quad (7)$$

The flow rate of lateral outflows at a certain angle α was determined as

$$Q_2 = Q_i - Q_1, \quad (8)$$

where Q_i is the total flow through the flume; Q_1 is the flow through the model in the absence of lateral outflows.

The throughput capacity of a water-containing shutter with flexible working bodies with a spillway part profile in the form of a rigid board was studied in detail by V. N. Shchedrin [11]. He derived an empirical dependence for determining the flow coefficient depending on the fixed elevation angle α of the board in the form $m = f(\alpha)$ without taking into account lateral outflows. According to his data, this flow coefficient varies within $m = 0.326 - 0.514$ [11].

Mathematical processing of the data of the research results obtained for a water-containing shutter with flexible working bodies and a spillway in the form of a rigid board in the absence of lateral outflows showed that the flow coefficient *m*, depending on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, varies according to the following quadratic parabolic dependence (Fig. 3)

$$m = 3.718\left(\frac{h}{H_z}\right)^2 - 3.371\frac{h}{H_z} + 1.095. \quad (9)$$

At $h/H_z = 0.19 - 0.5$, the flow coefficient varies within $m = 0.33 - 0.52$. In general, it is consistent with the studies of V. N. Shchedrin [11].

In the presence of lateral outflows, when the gap between the lateral walls of the flume and the lateral face of the shutter is 0.0035 m, its reduced flow coefficient mp, depend-

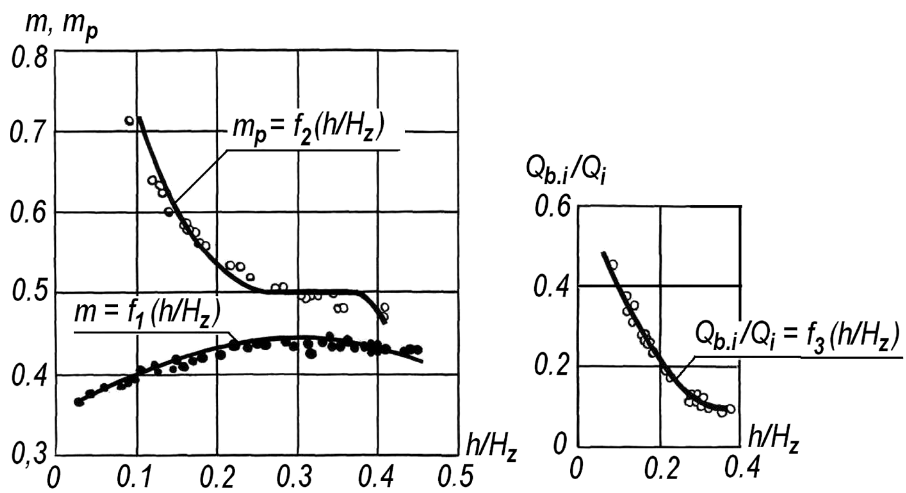

Fig. 4. Graphs of dependence $m = f_1(h/H_z)$, $m_p = f_2(h/H_z)$, $Q_{b.i}/Q_i = f_3(h/H_z)$ obtained for a water-containing shutter with flexible working bodies and a rigid spillway part in the form of a non-vacuum profile.

ing on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, changes according to the following cubic parabolic dependence:

$$m_p = 50.65\left(\frac{h}{H_z}\right)^3 + 55.567\left(\frac{h}{H_z}\right)^2 - 20.67\frac{h}{H_z} + 3.042. \quad (10)$$

At $h/H_z = 0.20 - 0.45$, the reduced flow coefficient varies within $m_p = 0.375 - 0.725$.

In addition, a quadratic parabolic dependence of the ratio of the flow rate of its lateral outflows $Q_{b.i}$ to the total flow rate Q_i passing through the flume, depending on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, was obtained:

$$\frac{Q_{b.i}}{Q_i} = 2.668\left(\frac{h}{H_z}\right)^2 - 2.822\frac{h}{H_z} + 0.711. \quad (11)$$

At $h/H_z = 0.18 - 0.5$, $Q_{b.i}/Q_i = 0.04 - 0.28$.

As a result of mathematical processing of the data obtained for the throughput capacity of a water-containing shutter with flexible working bodies and a rigid spillway in the form of a non-vacuum profile at $H_{pr} = 0.15$ m, without lateral outflows and at a fixed elevation angle of the chord of the shutter spillway part α, a parabolic dependence of the change in the flow coefficient m depending on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, described by Eq. (10) (Fig. 3), was obtained. At $h/H_z = 0.05 - 0.45$, the flow coefficient varies within $m = 0.37 - 0.45$. And for the case of the presence of lateral outflows, when the gap between the flume lateral walls and the shutter lateral face is 0.0035 m, a cubic parabolic dependence of the change in its reduced flow coefficient m_p depending on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, described by Eq. (11), is obtained (Fig. 4). At $h/H_z = 0.075 - 0.45$, the flow coefficient changes within $m_p = 0.775 - 0.45$. A quadratic parabolic dependence of the ratio of the flow rate of its lateral outflows $Q_{b.i}$ to the total flow rate Q_i passing through the flume, depending on the ratio of the geometric head over the shutter crest to the shutter height h/H_z, was also obtained (Fig. 4). At $h/H_z = 0.08 - 0.40$, $Q_{b.i}/Q_i = 0.1 - 0.5$.

As a result of the research, the authors have also built diagrams of hydrodynamic pressure acting on this water-containing shutter with a rigid spillway part in the form of a non-vacuum profile at various elevation angles of the chord of the shutter spillway part α (Fig. 5). They showed that for the entire range of elevation angles of the chord of the spillway part of the water-containing shutter, the hydrodynamic pressure on the spillway part has a positive value and the shutter operates without vibrations in a stable mode.

CONCLUSIONS

1. The hydrodynamic pressure acting on the spillway part of a water-containing shutter with flexible working bodies and a vacuum profile of the spillway part of an elliptical outline and with a spillway part in the form of a board at elevation angles of the chord of the shutter spillway part of more than 0.436 rad is characterized by the occurrence of reduced pressure, vacuum under the jet on the shutter crest, which leads to vibration and unstable shutter operation.

2. The hydrodynamic pressure acting on the spillway part of a water-containing shutter with a non-vacuum profile of the spillway part at any elevation angle of the chord of its spillway part on the crest and along its entire spillway part is positive, which leads to its stable operation without vibrations. Therefore, in practice, a water-containing shutter with flexible working bodies, which is part of the automatic water level controller [1], is recommended to be made with a spillway part of a non-vacuum profile.

3. Among the considered types of a water-containing shutter with flexible working bodies, a water-containing shutter with flexible working bodies with a vacuum profile of the spillway part of an elliptical shape has the highest throughput capacity. A shutter with a spillway part in the form of a board is on the second place, and only then comes the shutter with a non-vacuum profile of the shutter spillway part.

4. The formulas obtained as a result of the research for determining the flow coefficients without taking into account lateral outflows and the reduced flow coefficients taking into account lateral outflows allow determining the throughput capacity of water-containing shutters with flexible working bodies that have the shape of their spillway part in in the form of: a) a board; b) non-vacuum profile; c) vacuum profile of elliptical shape.

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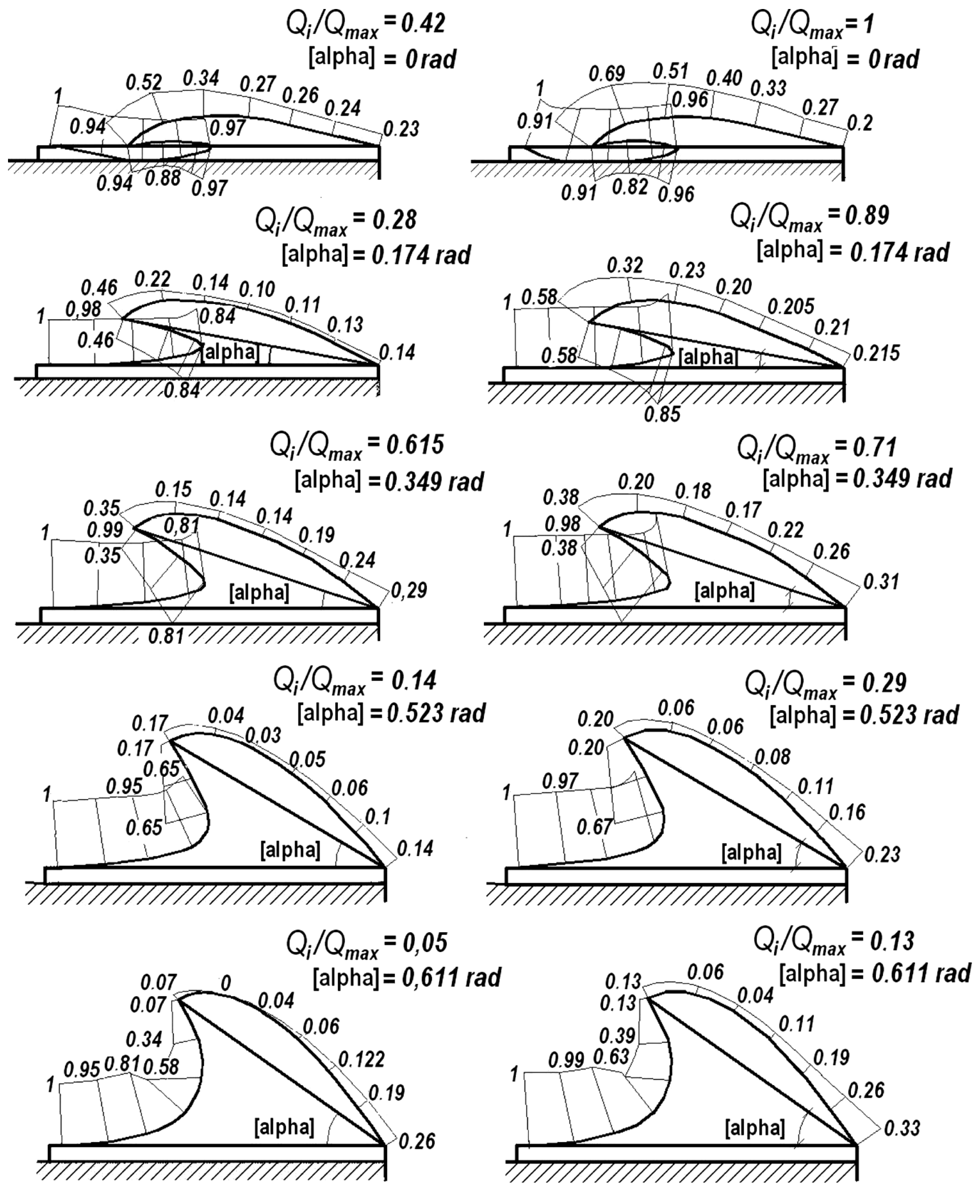

Fig. 5. Diagrams of the hydrodynamic pressure acting on a water-containing shutter with flexible working bodies and a rigid spillway part in the form of a non-vacuum profile at various elevation angles of the chord of the shutter spillway part α and the ratio of the flow rate of water moving along the flume Q_i to the maximum flow rate Qmax. The hydrodynamic pressure on the diagrams is shown as the ratio $p/p_{\max}$, where p is the hydrodynamic pressure at the shown point; $p_{\max}$ is the maximum hydrodynamic pressure on the water-containing shutter.

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