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EXPERIMENTAL DESIGN JUSTIFICATION OF THE SHORT-SPAN SPILLWAY'S TAIL-WATER DEVICES

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ABSTRACT

The article examines proposals for ensuring trouble-free and reliable operation of short-span spillway structures, which are widespread in reclamation systems of the Russian agro-industrial complex using the example of the Kursk complex hydroelectric complex. Is given an analysis of the results of hydraulic studies which evaluate the design solution for the devices of the outlet section of the three-span spillway of the hydraulic system that is expanding in terms of plan. Are presented the schemes of technical solutions proposed on the basis of experiments to find rational types of downstream devices that provide effective energy dissipation and prevent the formation of dangerous disruption currents. At the same time, the work of dampers and the entire outlet section was considered under various schemes of alternating open and closed spans of the spillway after its renovation.

Keywords: Downstream devices, Efficient energy dissipation, Flow failure.

INTRODUCTION

To one degree or another, a third of all registered emergencies and incidents at complex waterworks are associated with various violations and failures at spillways (Chernykh and Burlachenko, 2022). In addition to natural ones, risk factors can also include a number of man-made ones: design errors, non-compliance with technical regulations and operating rules, incompetence of maintenance personnel, lack of design documentation, insufficient completeness of hydraulic experimental studies or failure to take into account their recommendations for structures of a high hazard class (Burlachenko et al., 2024). For example, when designing and calculating justification for short-span spillway structures, due to their low hazard class and the lack of acceptable recommendations, the design and calculations of downstream devices are erroneously based on the same principles as for multi-span spillway dams (Rozanov, 1984). An analysis of the operating experience of such structures has shown that they operate in both symmetrical and asymmetrical flow modes. At the same time, in their tailwater there is very often a flow movement with a disrupted flow, leading to very unfavorable consequences (Volkov and Chernykh, 2019). Hydrobuilders encountered this problem during the renovation of the Kursk hydroelectric complex on the Tuskar River (1977-2013) (Fig. 1).

a)

b)

Figure 1: View of the reservoir: a) in winter, 2022 and the outlet section of the three-span spillway dam of the Kursk hydroelectric complex, b) in June 2024.

The spillway was designed in the form of a three-span spillway dam with a threshold of a practical profile, interfaced with the left and right bank parts of the earth dam. Clear span width b = 12 m, design spillway flow Q = 1020 m^3/s, specific flow along the dam = 28.4 m^2/s. In the downstream of the spillway, a concrete expanding water well was designed with a depth of 1.3 m and a length of 24.7 m, mating with a short apron 20.5 m long. At the end of the apron there is a bucket partially filled with rock fill. The well and apron have an expansion in plan with a socket angle $\theta = 7^0$ to the flow axis. At the base of the spillway lie alluvial deposits, represented by sands of different grains.

METHODS

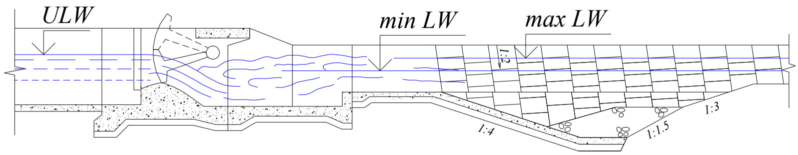
Hydraulic studies were carried out on a spatial model of the spillway at a scale of 1:45. The scale of modeling was chosen from the conditions of observing the basic laws of similarity under the prevailing action of gravity and ensuring self-similarity in terms of the Reynolds number, which varies in experiments in the range from twenty thousand to a hundred thousand. The studies were carried out in a wide range of changes in shutter maneuvering schemes. In all modes of passing flows through the spillway, the conjugation of the pools in the plan was recorded. Water levels, depths and elevations were determined by Spitzen scales (Snezhko, 2015). Careful measurements of current velocities were made using X-6 micro-spinners. During the studies, the averaged and pulsation characteristics of the flow in the downstream zone (velocities and pressure) were measured, respectively, using X-6 microspinners and strain gauges, piezometers and inductive pressure sensors and inductive pressure sensors with a receiving membrane diameter of 6 mm (Chernykh and Khanov, 2017). The throughput of the structure was determined by a triangular measuring weir and the hydrodynamic loads on the fastening plates were recorded using a cantilever-type platform sensor plate. For some fastening options on an eroded model made of expanded clay ash with an average particle diameter d_{50} <1.3 mm, the reshaping of the bottom behind the fastening was also studied.

RESULTS AND DISCUSSION

It was found that when the calculated flow rate is passed through three spans, the water well does not provide acceptable conditions for connecting the pools and uniform spreading of the flow on the apron.

There is a concentration of flow on the axis of the spillway directly behind the well. Thus, the ladle does not have a significant effect on its spreading (Fig. 2).

The current speeds are distributed unevenly, so at a distance of 90 m from the end of the well, the average speeds on the left bank are 3 times less than on the right. Bottom speeds in the area behind the bucket are 4 times higher than the permissible speeds for erosion.



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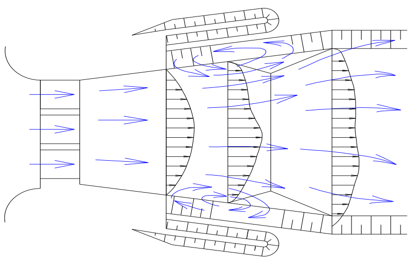

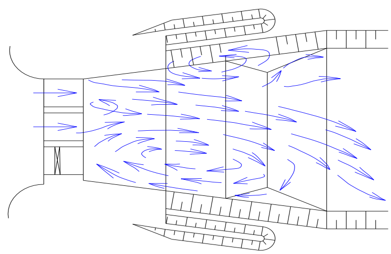

b c

Figure 2: Results of the study of the design option for the Kursk waterworks spillway: a –section along the axis of the spillway; b – flow pattern in the downstream with all gates open, *Q* = 1020 m^3/s; c – the same with two open gates *Q* = 680 m^3/s.

During the construction of the Kursk hydroelectric complex, only the second row of dampers was installed at the end of the water well (Fig. 3).

Figure 3: Operation of the constructed spillway of the first stage with two outer spans.

An uneven distribution of velocities was observed in all variants of maneuvering the gates on the apron and in the outlet channel. It was clear that in order to improve the hydraulic conditions of the downstream it is necessary either to equip the water body with spreaders (Burlachenko et al., 2023), checker dampers (Volkov and Chernykh, 2012), an additional water wall or to extend the gobies along the entire length of the water body, which after compressed section would represent separate walls. Examples of such structures are the Itaitsu (Brazil), Karuyuna (Iran), Tarbela (Pakistan), Podolsky and Krapivinsky hydroelectric spillways (Russia) (Chernykh et al., 2023).

One of the main reasons for the unsatisfactory performance of the design project is that instead of the expected coupling with an imperfect hydraulic jump, at the outlet section of the spillway there is a coupling with an imperfect jump-wave type. Such a jump usually occurs at small Froude numbers $Fr = V^2/gh$ (V, h are the speed and depth of the flow, respectively, the acceleration of free fall $g = 9.81$ m/s^2), is characterized by a high crest of the first wave and a chain of small waves that slowly decays along the length of the flow. In this case, whirlpool zones appear behind the reverse walls at the end of the water hole, which have a direct connection with the hydraulic jump zone at the water hole.

These whirlpools contribute to the compression of the transit flow in plan and the lateral flow of non-transit masses of liquid onto it. The faulty flow was especially clearly evident when the structure operated according to an asymmetrical discharge scheme with one or two spans (Fig. 2c). An analysis of the hydraulic operating conditions of the downstream of the spillway at all flow rates and maneuvering schemes showed that the water well does not provide the required conditions for connecting the pools and needs significant structural modification.

The apron and bucket also require similar design changes. It was noted that the lateral fastenings of the dam do not noticeably affect the interface of the pools and the spreading of the flow when the flow rate is less than the calculated one. They come into operation only when expenses with a security of 0.1% or lower are missed.

The main disadvantages of the design variant for the spillway under study were caused primarily by the fact that when developing its design, the designers used downstream elements that have proven themselves in the practice of designing and operating multi-span spillway dams.

The main parameters of the flow entering the waterway at the Froude number $Fr_1 = 8.8$ under various operating conditions of the spillway in question are given in Table 1.

Table 1: Flow parameters at the water body of the Kursk hydroelectric complex in condition of maneuvering the gates

Number of open spans	Degree of jet expansion $\beta = B/b$	shape Factor $N = b/h_1$	Non-symmetry of the jet entry to the water outlet Coefficient $e = c/0.5B$
All spans	1.54	17.14	0.143
Two adjacent spans on the left	3.08	11.42	0.459
Two extreme spans on the left and right	3.08	11.42	0.133
Two adjacent spans on the right	3.08	11.42.	- 0.153
One left	4.63	5.71.	0.591
One average	4.63	5.71	0.163
One right	4.63	5.71	- 0.489

In the table:

B = width of the outlet section;

b = span width;

h_1 = flow depth in the compressed section

To eliminate the jump-wave within the fastening, a number of options were considered for installing a wall with an inclined jagged or solid front face at the end of the water well. These studies made it possible to establish that a wall with a jagged, inclined front face works most effectively (Fig. 4). In addition to the wall, systems of flow dampers and spreaders were selected, similar to those used in the design of the Podolsk spillway and the Shamkir hydroelectric complex (Chernykh et al., 2023). In addition, the following damper systems were studied: spreaders with different angles of rotation, checker dampers and a water wall (solid and serrated); spreaders, water threshold and wall; spreaders, narrow water sills and wall; spreaders, slotted wall and curved wall behind the well, etc. (Lappo, 1988).

It has been established that the angle of rotation of the spreaders and the distance between them significantly influence the conditions of flow spreading. The most rational was the layout of the spreaders, shown in Figure 4. It was found that the best results are shown by the options with the top edge of the wall (up to $0.3h_2$ in height, h_2 is the depth in the downstream), located at the outlet of the well, $m = 2$.

In this case there is no phenomenon of flow division into two jets with significant velocities along the slopes of the outlet section. The results obtained are fully consistent with data from the US Bureau of Reclamation (Volkov and Chernykh, 2012).

However, we have to admit that the proposed designs are a little cumbersome for practical use. Lengthening the bell part of the well beyond the water wall and slightly increasing the central expansion angle of the retaining walls improves the conditions for flow spreading behind the fixture (Chernykh and Burlachenko, 2023).

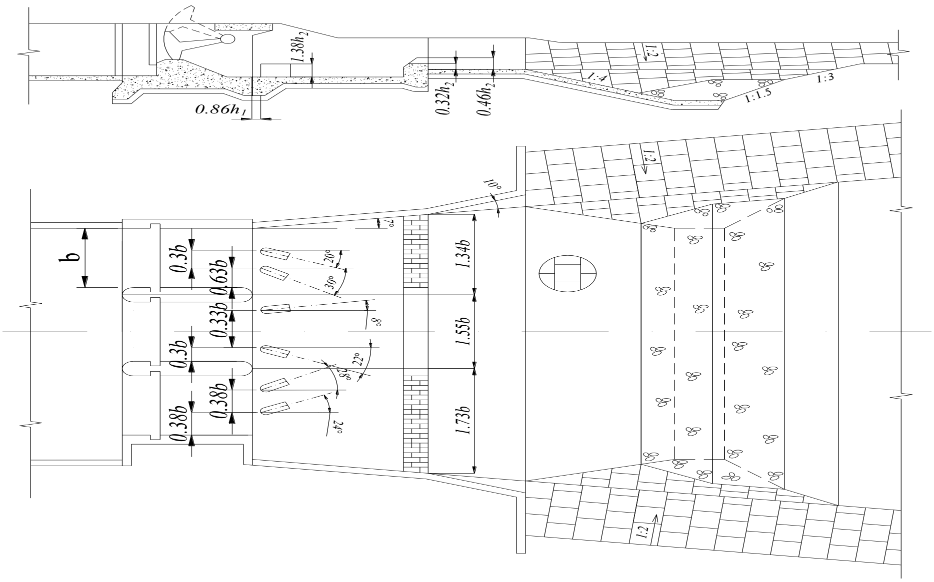

Figure 4: Structural design of the downstream structures of the Kursk hydroelectric complex, developed based on the results of model hydraulic studies.

When all spans or one middle span are opened, flow velocities in the area of the left-side slope of the outlet channel increase, and a disruption flow occurs. When the calculated spillway flow passed, standing waves were observed behind the wall on the axial part of the flow.

The height of the waves propagating to the middle of the bucket reached 1 m, and the length was at 10 to15 m. The occurrence of these waves changed the operating conditions of the apron slabs. To eliminate this phenomenon, it was enough to reduce the height of the wall in the middle part of the well and make it non-slotted.

By changing the angle of rotation of the spreaders, it was possible to significantly reduce the flow speed at the left-side slope of the outlet channel.

Analysis of the velocity diagrams showed that the final spreader arrangement (Fig. 4) ensures good flow spreading at all openings.

Even with an increase in the coefficient of non-symmetry of the jet entry to the water outlet (Table 1) at 0.459 to 0.591, that is, with the opening of two left adjacent or one left span, there was quite favorable flow spreading in the outlet channel (Figs. 5 a, 5b).

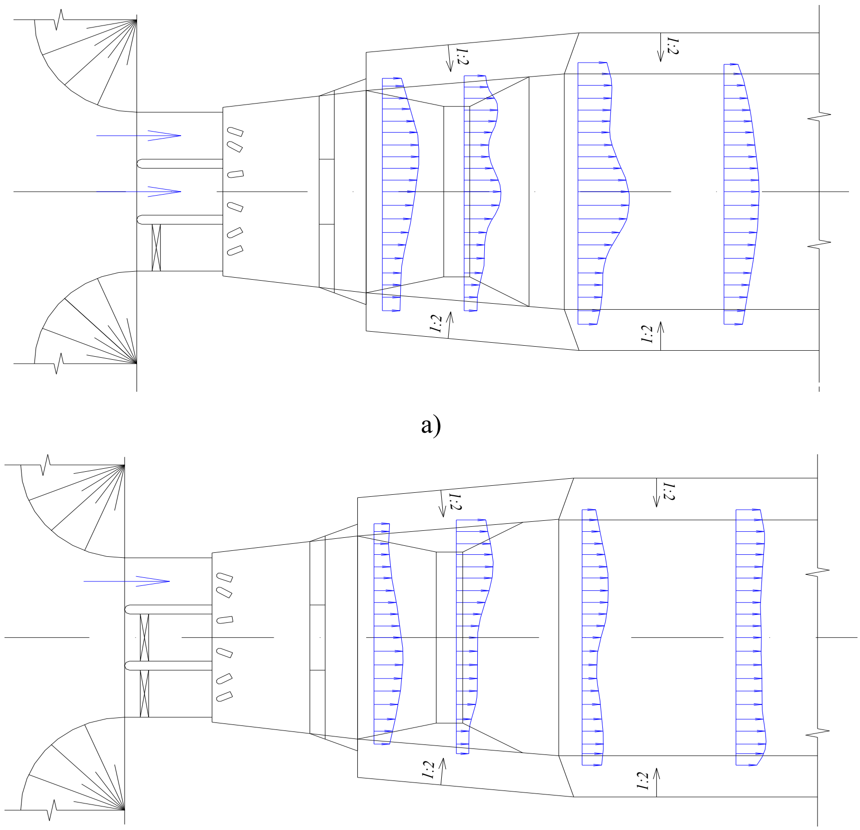

Figure 5: Schemas of flow plans with flow velocity diagrams when two (a) and one (b) spans of the spillway are opened with the proposed scheme of damping devices at the water body applied

Looking at the graph of changes in speeds on the spillway axis V_{max}/V, where V_{max} is the maximum bottom speed, V is the average speed on the axis (Fig.6), it is clear that the proposed spillway design variant works better than the design one in almost all maneuvering schemes.

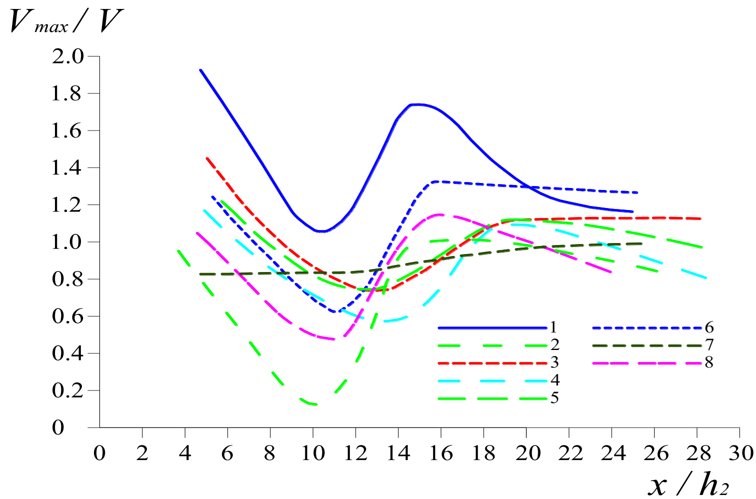

Figure 6: Graphs of changes in relative maximum bottom velocities *Vmax/V* on the spillway axis: 1 and 2 – all spans are open; 3 – the first span is open; 4 – the second span is open; 5 – the third span is open; 6 – two extreme spans are open; 7 – the first and second spans are open; 8 – the second and third spans are open

The results analysis of measuring hydrodynamic loads on the fastening slabs made it possible to establish that in order to increase the stability of the water breaker and apron slabs and ensure minimum filtration pressure under them, it is necessary to construct drainage wells behind the spreaders in the zone of maximum pressure deficit (Chernykh, et al., 2023).

To prevent the penetration of pressure pulsations through these wells under the water tank slabs, taking into account the increased pressure pulsations in the area near the bottom, wells made of porous concrete are recommended (Burlachenko et al., 2024). The existing reconstructed spillway does not currently have spreaders or drainage wells. This fact limits the further operation of the entire spillway.

Soil transformation studies conducted at the bottom behind the spillway with the designed waterway section were carried out for two modes of its operation: when the design flow rate of 1020 m^3/s passed and when the structure was operating with one left span with a flow rate of 340 m^3/s.

It was found that the maximum depth of erosion at the calculated flow rate reaches 7 m, and the focus of erosion will be at a distance of 43 m from the end of the concrete fastening. Erosion occurs mainly on the axis of the outlet channel; the slopes are eroded to a much lesser extent, since they are protected by stone filling. With asymmetrical operation of the spillway, the depth of the funnel reaches 2.8 m, and its focus is located 20 m from the end of the fortification.

To further improve the designs of fastening devices for open short-span structures, as well as to develop new methods for calculating justification of the parameters of damping devices, it is necessary to continue laboratory and field studies of the hydraulic and dynamic operating conditions of their tailwaters.

CONCLUSION

Based on laboratory studies, it has been established that the design variant of the outlet tailwater section, along which the spillway of the Kursk hydroelectric complex is built, does not eliminate flow failure in the outlet channel even when the structure is operating in full front.

An option for installing additional flow spreaders on the water body was experimentally selected and tested. The proposed solution to the problem of increasing the operation reliability of the entire hydraulic system during its renovation, associated with erosion in the downstream and the need to increase the water level in the reservoir to the design level, ensures a uniform distribution of unit costs at the end of the fortified section behind the spillway.

The conducted model hydraulic studies made it possible to establish the features of changes in the diagram of maximum flow velocities, to analyze fluctuations in the water level in the outlet channel for various options when passing discharge flows with symmetrical and asymmetrical gate maneuvering schemes.

When designing fastenings behind short-span structures are located in relatively narrow tailwaters, it should be taken into account that individual structural elements of fastening, which have proven themselves in the operation of multi-span structures (for example, buckets behind an apron), in a particular case may turn out to be ineffective, and at relatively high specific consumption in general are unacceptable and can be completely filled with rock during repairs, sometimes with lengthening of the strengthening area up to the entire short channel being filled with small stone filling.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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