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OPERATION EVALUATION OF WATER DISCHARGE END SECTIONS IN THE CONDITIONS OF NARROW DOWNTHROW

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ABSTRACT

This article presents and discusses the results of model studies of culverts of high-pressure waterworks with a narrow tailwater, which were not taken into account in the design, construction and operation of the Kurpsai waterworks in Kyrgyzstan. The incorrectly developed design of the downstream devices significantly complicates the operation of the hydroelectric complex after its construction and renovation and leads to the creation of a possible emergency situation both at the hydroelectric complex itself and at the hydropower cascade, of which it is a part. The results of model hydraulic studies of the end sections of spillways with free-falling jets of high-pressure waterworks are presented. A comparative assessment of the use of various designs of downstream devices is given: erosion-free dampers in an expanding water-breaking area with different flare angles and various modified schemes of springboards for the parameters of the washout funnel in the outlet channel in relation to the terminal device of the surface spillway of the Kurpsai hydroelectric power station on the Naryn River in the Kyrgyz Republic.

Keywords: Deep spillway, Downstream, Energy dissipation, Springboard toe, Washout funnel

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INTRODUCTION

In hydraulic studies of both open and closed spillways of high-pressure waterworks, methods for modeling the phenomena occurring in them are used most widely since theoretical solutions to hydromechanical problems when evaluating the operation of such hydraulic structures are quite difficult to correctly perform (Chernykh and Burlachenko, 2021; Rozanov, 1984; Oleinikova, 2011). Therefore, model studies of the design version of the spillway structures of the Kurpsai hydroelectric complex in the 1980s were conducted in the hydraulic laboratory of the Moscow Irrigation Institute under the guidance of Prof. Doctor of Technical Sciences. Rozanov N.P. The features of the operation of the end devices of the spillway operating in conditions of a very narrow downstream were given recommendations for their solution but were not taken into account during its construction and further operation (Fig. 1) (Rumyantsev and al., 2012; Trofimtseva, 2012). As a result, at the beginning of the 21st century, during the work of the already built and put into operation Kurpsai hydroelectric complex, they again sharply arose and required not only additional hydraulic studies but also the solution of a number of production, operational and other costly problems during the renovation and repair of the hydraulic system of the hydroelectric complex (Madumarov et al., 2018; Madumarov and lavrov, 2017; Chernykh, 2020; Volkov and Chernykh, 2012; Morris, 1969).

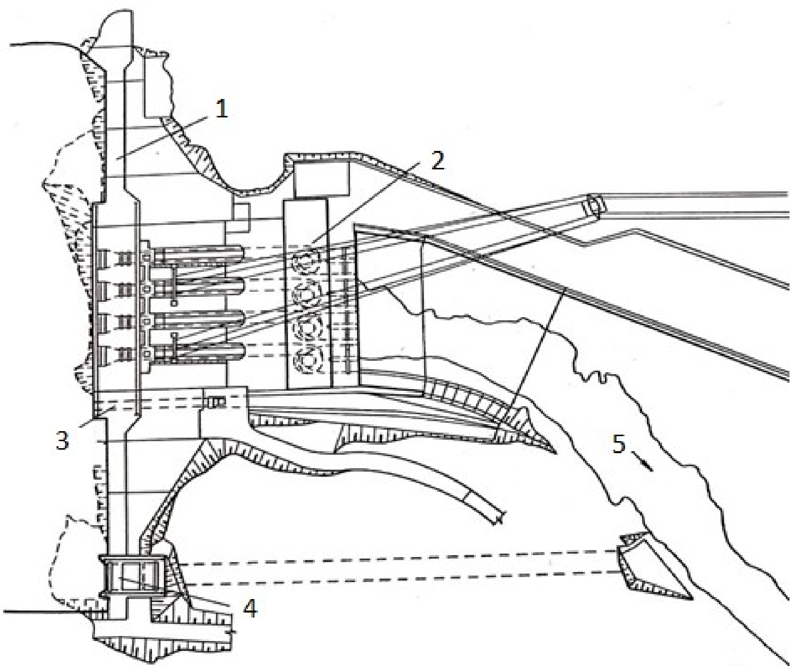


Figure 1: Master plan of the Kurpsai hydroelectric complex: 1 - concrete dam; 2 - HPP; 3 - deep spillway; 4 - surface spillway; 5 - Naryn River

CURRENT SITUATION IN THE KURPSAI HYDROELECTRIC POWER STATION

Kurpsaysky hydroelectric complex with a gravity dam 113 m high, with built-in surface and deep spillways (Fig. 2), a water intake, turbine conduits, outdoor switchgear 110 and 220 kV and 4 units with a capacity of 800 MW is part of the cascade of hydroelectric power plants (HPP) on the Naryn River and provides electricity not only to Kyrgyzstan but also to neighboring states - Kazakhstan, Uzbekistan, China. Water from the Naryn River is mainly used for irrigation. The operating main surface spillway of this hydroelectric complex has one span 16 m wide with a gradual narrowing to 10 m in plan to the outlet tunnel.

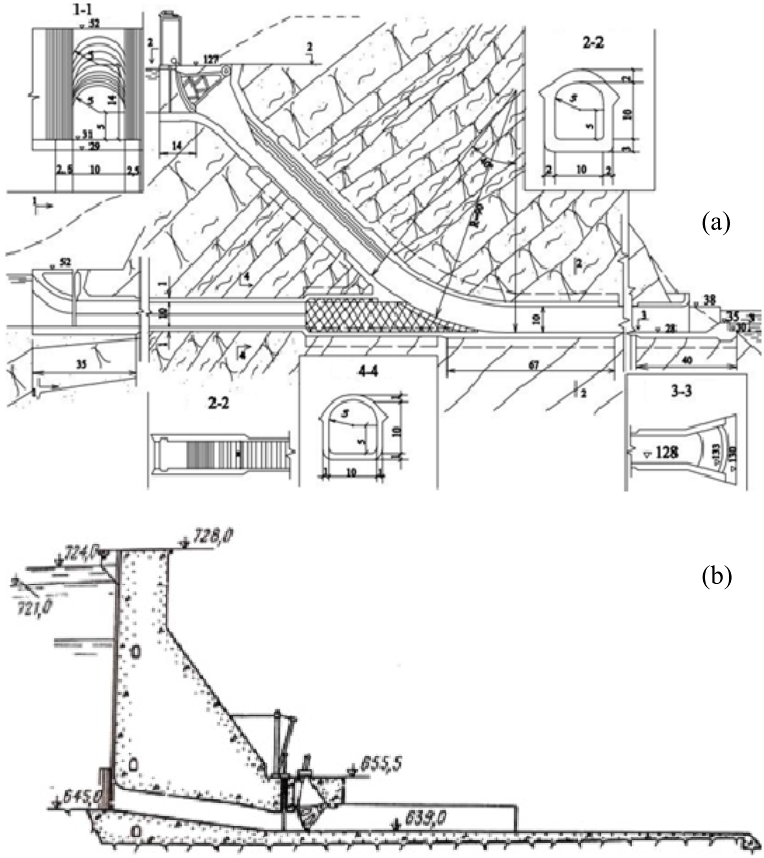


Figure 2: Sections along the spillways of the Kurpsai hydroelectric complex: a - surface; b – deep

The Kurpsai hydropower plant is located 40 km downstream from the Toktogul HPP. The base of the dam of hazard class I is composed of interbedded sandstones and mudstones with a steep dip toward the upstream with a cohesion of 0.3 MPa. When designing the dam of the Kurpsai HPP, for the first time in the former USSR, special design solutions were developed to improve its manufacturability: spillway structures (a deep spillway designed for a water flow rate of 1074 m3/s and a surface spillway for a flow rate of up to 1680 m3/s at the normal water level (NWL) are placed in the local zone in the right-bank junction, and 4 lines of turbine conduits are placed on the downstream side of the dam (Fig. 3).

Figure 3: View of the outlet heads of the surface and deep spillways of the Kurpsai HPP + (1976-1986) located in a narrow gorge

Over the years of operation at the Kurpsai hydroelectric complex, emergency situations have repeatedly occurred: cavitation destruction of the walls of the outlet tract behind the shutter chamber of the deep spillway (Trofimtseva 2009; Madumarov and al 2018; Madumarov and lavrov 2017), shutdown in 2012 of outgoing 220-110-6 kV overhead lines and a fire at the autotransformer due to the impact of spherical lightning and bank erosion, the throughput ability of which did not correspond to the design (Fig. 4).

Discharges of excess water and later field studies of a surface spillway, the end section of which was a slab in the form of an irregular convex polygon, equipped with three springboards expanding in plan, showed (Trofimtseva 2009) that the spillway does not allow using water discharges exceeding 450 m3/s. So as with large discharges of water, the length of the stream and water dust discharged from springboards significantly exceeds the design characteristics, reaching 180 m, which is approximately 2.3 times more than the design limit values.

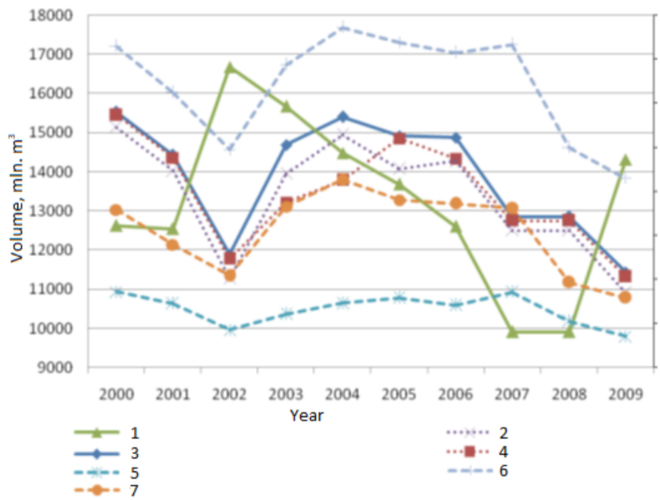
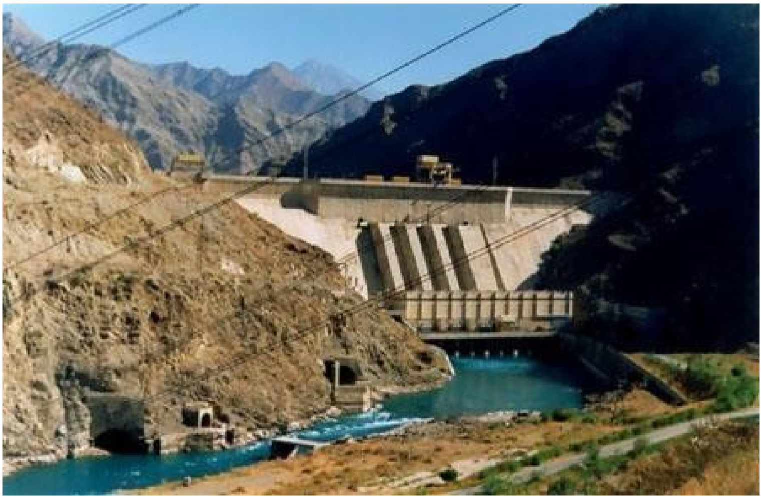


Figure 4: The combined schedule of inflow and consumption of electricity by the Kurpsai (KGPP) and Toktogul (TGPP) hydroelectric power plants of the Naryn cascade: 1- inflow to the site of the THPP; 2 - flow through the hydroelectric units of the THPP; 3 - inflow to the alignment of the KHPP; 4 - flow through the hydroelectric units of the KHPP; 5 - generation of KHPP; 6 - development of the cascade; 7 - generation of THPP

This leads to water saturation of the left slope of the narrow Naryn River, and the occurrence of landslides downstream of the structure causes the washing out of the power transmission line 220 support and the penetration of the water flow thrown from the springboards into the power cable trench, threatening to create an emergency in the entire energy system of the HPP cascade (Fig. 5) (Madumarov et al., 2018; Madumarov and lavrov, 2017; Chernykh 2020; Volkov and Chernykh, 2012; Morris, 1969). Comparison of the planned distribution areas of a compact jet and air droplets confirmed the "adequacy" of the processes occurring in nature and on models, revealing significant shortcomings in the design and operation of spillways, especially with an increase in discharge flow rates of more than 600 m3/s, when the dynamic axis of the flow deviates to the left along the course of the water flow, significantly expanding the impact area, in the zone of which there are power lines. In addition, it was established that it was necessary to reconstruct the spillway structures of the Kurpsai hydroelectric complex, especially the end part of the surface spillway, to change the trajectory of the jet thrown from the springboards of the spillway. Patented proposals were even developed for variants of extinguishing devices with a sidewall - a limiter, which made it possible to reduce the propagation length of the compact jet by 1.8 times and place it practically in the channel of the Naryn River (Trofimtseva, 2009; Volkov and Chernykh, 2012).



(a)

(b)

Figure 5: General view (a) and full-scale tests (b) of the surface and deep spillways of the Kurpsai HPP under contracts concluded with the Cascade of Toktogul HPPs, 2004-2011

Since the countries of Central Asia also intend to strengthen further cooperation and develop joint activities to ensure the safety of hydraulic structures, it seems relevant to analyze the historical aspect of the experience of studying the main transboundary energy facilities.

METHODS

To prevent the possibility of an emergency situation at the hydroelectric complex and the Lower Naryn cascade as a whole, experimental studies were carried out on an eroded model of the end section of the main spillway with 8 design options for extinguishing devices (Fig. 6). Calculations of individual elements of the culvert were performed according to various methods published in the special literature (Rozanov, 1984; Morris, 1969; Salnikova, 1958; Guryev and al., 2021; Chernykh and Komelkov, 1983; Lappo, 1988).

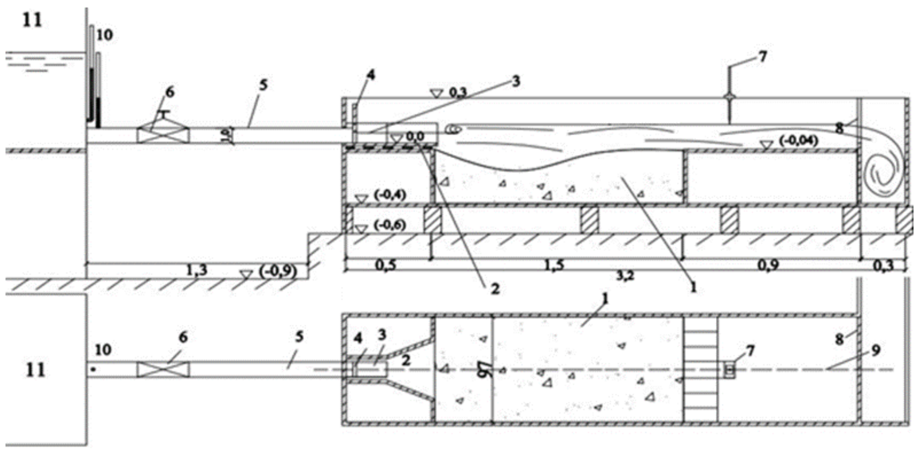
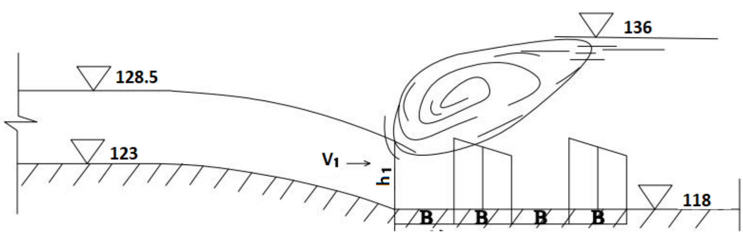


Figure 6: Section and plan of model installation: 1 - cassette with crushed stone; 2 - socket walls; 3 - transitional section; 4 - control gate; 5 - inlet pipe *d* = 10 cm; 6 - valve; 7 - measuring needle; 8 - groove for stopors; 9 - waste tray; 10 - piezometers; 11 – tank

Studies with a linear scale factor α_l = 125 were carried out according to the law of gravitational similarity with self-similarity of the phenomena under consideration according to the Reynolds criterion for two periods: operational and construction, at constant flow rates and depths downstream, respectively, on the model: flow rate Q = 10.8 l/s, downstream water depth h_2 = 14.4 cm and Q = 4.8 l/s, h_2 = 7.4 cm. In this case, the Froude number was determined as $Fr = \upsilon^2/gh$, where υ is the average flow velocity; g is the free fall acceleration or the acceleration due to gavity; and h is the depth of the flow. The studies were carried out in the following order: the structure under study was installed; the tray was prepared (the crushed stone was leveled and compacted, then it was covered with a film, and the correct installation of the scales and equipment was checked); and water was added to the tray. The flow rate was determined by a triangular weir with a thin wall with an angle at the top of 900. When the estimated flow rate and water level were established, the film was removed, and the model worked for 1.5 hours (previously experimentally substantiated stabilization time of the washout funnel). During the work, control measurements of the jet departure length, washout depth, a description of the nature of the conjugation (splashing, flow spreading in plan, etc.) were made, the flow was photographed and sketched. At the end of the experiment, using the Spitzen scale, the longitudinal and transverse profiles of the formed funnel were recorded (along the axis with the maximum erosion depth). The issue of the effectiveness of a particular design was decided on the basis of a comparison of options for the least erosion of the base and a not too long departure length (maximum - 80 cm on the model, given that in nature with a longer departure length, the jet can, falling, destroy the left bank of the Naryn river) and the best hydraulic picture of the conjugation of the pools.

RESULTS AND DISCUSSION

In these studies, two basic schemes of downstream devices were considered (Fig. 7): schemes of the "I" series - energy damping using nonerosion checker-type dampers with and without a well (schemes No. 1 and 2) and schemes of the "II" series - with the help of springboard socks (5 designs with flow splitters No. 4 - 8 and without it - No. 3). The use of checkers first of 1 row and then when installing 2 rows of erosion-free outline was because the flow velocities in the well could be approximately 25... 30 m/s, which creates conditions for the occurrence of cavitation and cavitation erosion, the consequence of which there may be damage or destruction of energy absorbers. The dimensions of these "supercavitating" absorbers were selected according to the calculation method proposed by N.P. Rozanov and developed later in more detail by his students [Oleinikova, 2011; Lappo, 1988; Chernykh and Burlachenko, 2022). Experiments with socks No. 3 and 4 were carried out for a comparative assessment of the work of the studied sock splitters. In all experiments of scheme “a”, the socket walls were vertical at first at the socket angle θ = 10°. Such an angle of the socket is close to the angle of natural flow spreading. However, when installing springboard socks, it became necessary to increase the flare angle to θ = 24°30′ to ensure flow spreading. This was clearly seen in the experiment with a socket without a toe (No. 3) and a triangular toe-springboard with an elevation angle β = 300 (No. 4), when at θ = 10°, the flow is squeezed onto the vertical walls and spontaneously overflows through them. The outlines of sock shapes No. 6 and No. 7 were adopted based on the results of studies conducted by N.F. Salnikova in MISI (Salnikova 1958), and for parabolic toe No. 8 – by Chanishvili and Vysotsky (Chernykh 2020; Lappo 1988; Altunin and al 2016).



(a)

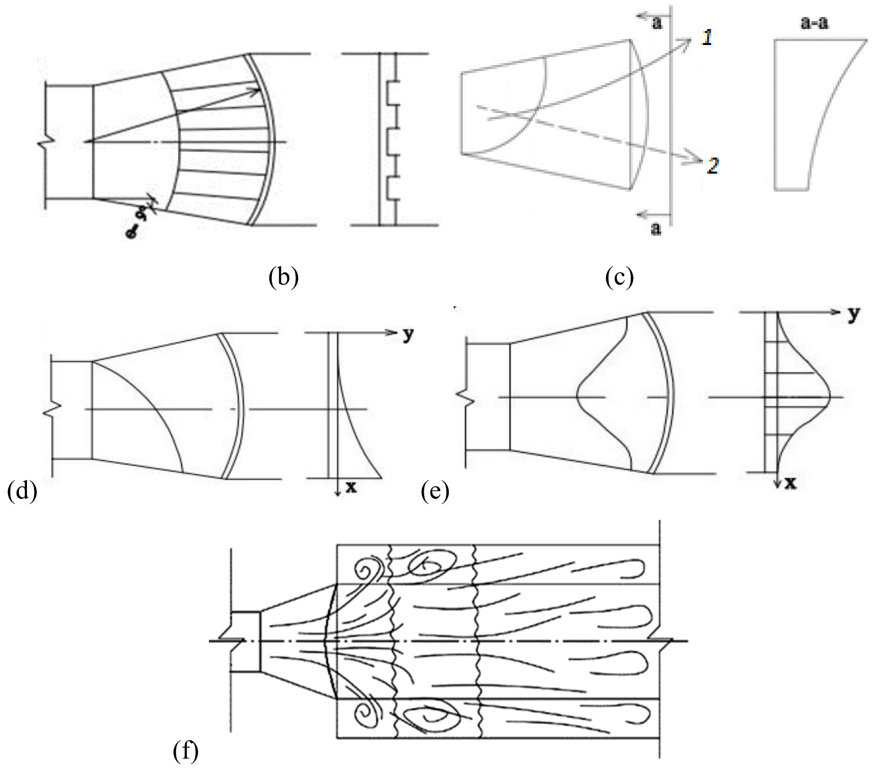


Figure 7: The main schemes of the investigated end sections: a - nonerosion checkers of the 2nd row (scheme No. 2); b - notched toe with a springboard (scheme No. 5); c, d – cosine toe splitter (No. 6); e - spoon-shaped sock (No. 7); f - parabolic toe (No. 8): 1 - actual direction of flow; 2 - the intended direction of flow

A series of model studies and an analysis of the erosion pattern behind the structure showed (Fig. 8) that out of all the considered options of series I, a design with erosion-free checker dampers installed in 2 rows could be recommended for practical use for the conditions of the surface spillway of the Kurpsai HPP (Fig. 8a, scheme No. 2b), which provides satisfactory hydraulics of the flow and the minimum depth of the washout funnel (Guryev and 2021; Lappo 1988; Hager and al 2021).

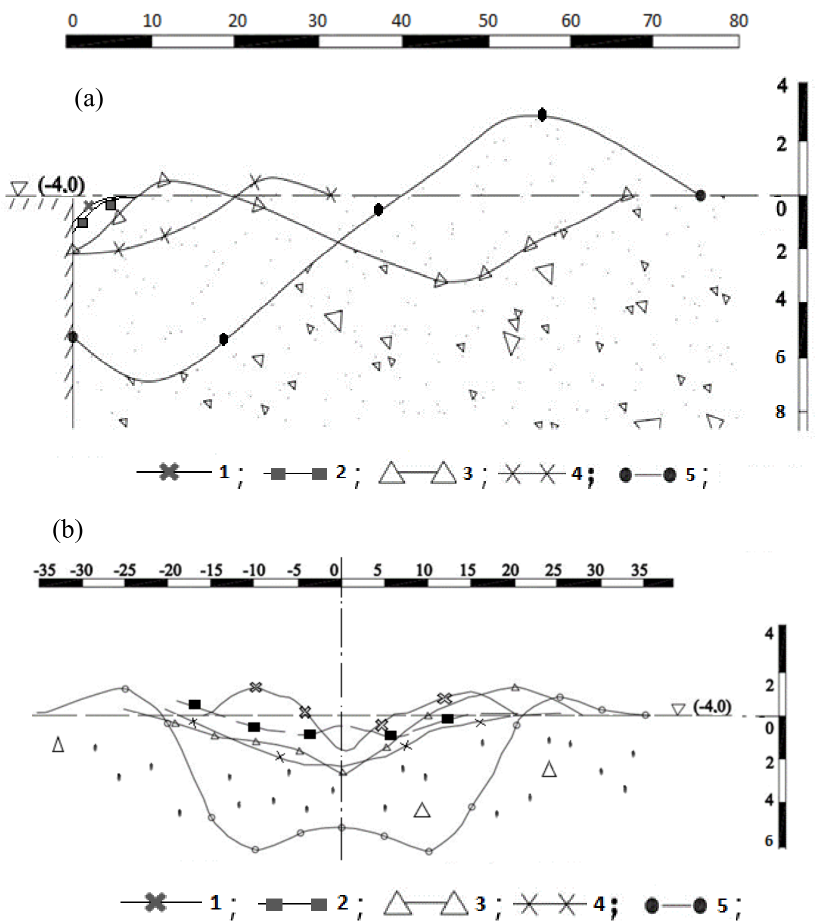


Figure 8: Longitudinal (a) and transverse sections (b) along the line of maximum erosion of the funnel behind the outlet funnel for experiments of series I: 1 - well without checkers; 2 - one row of checkers at the end of the bell; 3 - checkers in 2 rows at an equidistant distance from each other; 4 - 2 rows of checkers installed in accordance with the calculation (scheme No. 2)

However, when constructing a water well, a difficult question arises about the location of the well in nature, the sequence of its construction, the possibility of increasing the length of the tunnel route, etc., since it is not advisable to push the well into the tunnel due to the difficulty of the work and the complex hydraulic regime in it.

Modeling studies once again confirmed that for spillways of high-pressure hydroelectric facilities located on a solid rocky foundation, it is often more profitable to use an expanding springboard, which allows you to sharply expand the turbulent flow and throw it a long distance from the hydraulic structures and the alignment of the hydroelectric complex. In the example of the spillway of the Kurpsai HPP, designed to pass floods from the reservoir to the downstream at the design flow rate Q = 1037 m^3/s, the falls are many times (5...10 times) reduced, which leads to a corresponding decrease in the depth of the erosion funnel. This is also facilitated by the fact that the expanding jet is significantly aerated and crushed, which reduces the specific flow rates due to an increase in the cross-sectional area of the jet at the point of impact, and the use of flow splitters significantly reduces the force impact of the flow on the channel, and almost no washouts are observed.

Experiments have shown greater efficiency of splitter socks, especially cosine (No. 6) and parabolic (No. 8), outlined taking into account the equally spaced plan of jets of surface streamlines. Nose No. 6 design deforms the flow to such an extent that its impact on the downstream bottom is minimal, and the specific flow rate at the downstream level decreases

by almost 4 times compared to the specific flow rate in the outlet section of the tunnel. In addition, due to the horseshoe shape of the wake, the specific discharges at the level of the downstream horizon will be even less (Fig. 9). There were practically no erosions and bottom reshaping on the model behind these structures.

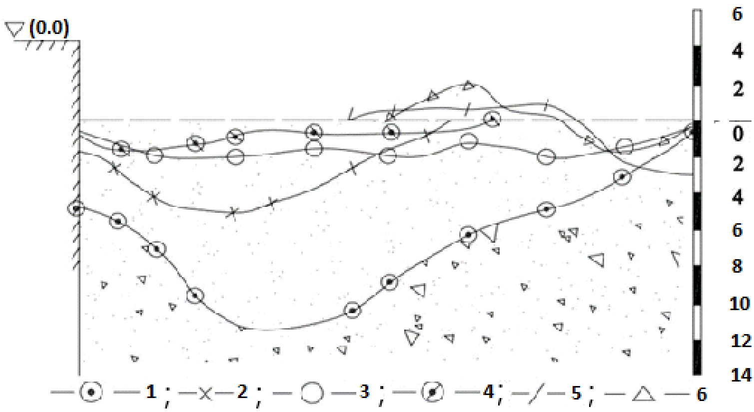


Figure 9: Longitudinal sections along the line of maximum erosion of the funnel behind the outlet funnel for experiments of series II: 1 – smooth funnel, θ= 100; 2 and 4 - nonerosion dampers at the bottom of a horizontal socket at θ = 100 (scheme 2); 3 – spoon-shaped toe at θ = 24°30′ (scheme 7); 5 and 6 - triangular springboard at β = 300, respectively, at θ = 100° and θ = 24°30′

However, the effectiveness of spoon-shaped nose No. 7 with an increase in the kinetic parameter and the height of the fall of the jet, which in the studies of a number of authors (Rozanov 1984; Madumarov and Lavrov 2017; Salnikova 1958; Lappo 1988; Zombrana, 1965; Hager and al., 2021) enhanced the effect of jet swirling, and intensification of its aeration was not confirmed for the conditions of the Kurpsai hydroelectric complex. When installing sock No. 7, the water, due to the high level downstream, squeezed the jet from the right edge of the sock with a lower height of the springboard. Its compact jet, falling, deviated quite strongly from the flow axis to the port side of the flume, reaching a length of approximately 80 cm (i.e., with a given design relatively high water horizon, the opposite effect turned out - the jet deviated not to the expected starboard side). In this case, a rather poor spreading of the flow in plan was observed, and the jet eroded a funnel of great length up to l = 100 cm in trench type with a depth of up to 3 cm.

Based on the research, it was recommended to adopt the design with a parabolic expanding nose No. 8 as the main option, as the most economical, simple in terms of work, very effective, giving a good interface with the downstream with little or no formation of a scour funnel and, importantly for a narrow downstream, with a short jet length. This made it possible to deliberately not provide a flow rejection with a strong jet deviation away from the axis of the outlet tract due to the possibility of washing away the left bank of the Naryn River, which had to be done in view of the small width of the gorge in the area of the exit portal of the tunnel when using other designs of splitter socks, including those made in accordance with the project during the construction of the hydroelectric complex, which was confirmed by the further practice of joint operation of the surface and deep spillways of the Kurpsai HPP (Lavrov et al., 2008; Rumyantsev et al., 2012; Chernykh, 2020).

CONCLUSION

Thus, it has been confirmed that one of the main ways to solve the problem of dissipating excess flow energy for high-pressure waterworks is to use springboard socks of various modifications at the end of spillways. To reduce the intensity of erosion and avoid significant hydrodynamic loads at the end section of the spillway, it is most effective in narrow sections to have a springboard with a zero or slight reverse slope. The use of jet splitters (scattering turns, etc.) can be recommended for use in all cases if their device is not contraindicated by operational considerations (undesirability of the formation of a significant amount of water dust, splashes, etc.), which requires additional modeling studies and justifications.

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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