Larhyss Journal, ISSN 1112-3680, n°63, Sep 2025, pp. 175-191

HYDRAULIC PERFORMANCE ASSESSMENT OF SPILLWAY NO 2 AT BOGUCHANSKY HYDROPOWER PLANT (RUSSIA) DURING THE CONSTRUCTION STAGE

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Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received October 5, 2024, Received in revised form September 1, 2025, Accepted September 3, 2025

ABSTRACT

This study presents a comprehensive hydraulic assessment of Spillway No 2 at the Boguchansky Hydroelectric Power Plant (Russia Federation), focusing on its operational performance during the construction period when incomplete structures may lead to atypical and potentially hazardous flow conditions. The investigation analyses the behaviour of river discharges through the spillway under both free overflow and pressurized flow regimes, employing theoretical formulations and hydraulic design standards to evaluate flow parameters, energy dissipation capacity, and jet formation characteristics.

Emphasis is placed on determining the conjugate depths of the hydraulic jump, Froude numbers, velocities, and discharge coefficients under varying reservoir levels and gate opening configurations. Particular attention is given to the limitations of the existing stilling basin, where calculations reveal that its current dimensions may be insufficient to contain the jump under pressure discharge conditions. The study further quantifies the trajectory, depth, and velocity of the high-energy jet that forms when the hydraulic jump cannot be fully stabilized, highlighting the risk of downstream erosion and structural impact.

Recommendations include the elevation of side walls to contain jet dispersal, reinforcement of downstream protection works, and consideration of energy dissipation measures adapted to transitional operation stages. The findings offer critical guidance for the design and temporary operation of hydraulic structures during phased development and contribute broadly to the safety assessment of large-scale hydropower installations.

Keywords: Hydraulic Constructions, Hydraulic Structures, Stilling Basin, Energy Dissipation, Spillway, Velocity, Discharge, Hydraulic jump, Water jet trajectory, Boguchansky HPP.

INTRODUCTION

In large-scale hydraulic engineering projects, such as hydroelectric power plants (HPPs), the design of spillway structures is of particular importance, ensuring the safety of construction and operation of waterworks, solving environmental problems of embedding hydraulic structures in the natural environment. During the construction and commissioning phases of such projects, temporary operational conditions can create atypical stress scenarios for hydraulic structures. Careful study of these operating conditions makes it possible to avoid erosion of the riverbed downstream, and to choose an effective way to dampen the excess kinetic energy of the discharged water to prevent structural failure.

The issue of energy dissipation on the spillways has been extensively investigated using the example of installing stilling basin, by jet throwing away from the structure, by using stepped spillways for dissipation along the entire length of the spillway structures.

Hydraulic jumps are essential for dissipating energy in open channel flows, especially downstream of spillways. The proper control and spatial optimization of hydraulic jumps are critical to ensure structural safety and reduce construction costs. Furthermore, recent years have witnessed a renewed interest in optimizing hydraulic jump stilling basins, particularly those designed with non-conventional geometries to improve energy dissipation and minimize structural erosion. Numerous studies have explored the effects of varying stilling basin shapes - such as rectangular, trapezoidal, and compound cross-sections - on the behaviour, location, and efficiency of hydraulic jumps (Amara et al., 2019; Benmalek et al., 2022; Achour et al., 2022a; 2022b; Achour and Amara, 2023). Similarly, Bouriche et al. (2023) combined physical modelling with machine learning techniques to assess velocity distributions in compound channel stilling basins. Their research emphasizes how basin shape and side-slope configuration influence turbulence intensity and jump reattachment length, particularly under supercritical flow regimes. An earlier foundational work by Achour et al. (2002) exploring how a sill can be used to position and regulate a hydraulic jump within a stilling basin of different shapes, combining theory and practical experimentation for energy dissipation applications. This study underscores the importance of tailored stilling basin designs that respond to both hydraulic conditions and geometric constraints. Collectively, the aforementioned contributions highlight a trend toward integrating empirical, numerical, and AI-based methodologies to improve the design and performance of hydraulic jump stilling basins in modern hydraulic engineering practice.

On the other hand, Benabdesselam et al. (2017) presented a comprehensive theoretical and experimental investigation into the behaviour of hydraulic jumps in compound channels - a topic that had received limited attention in prior literature. This research addresses a significant gap in hydraulic engineering by exploring the characteristics of hydraulic jumps in rectangular compound channels, rather than traditional single-section channels. Compound channels are more representative of real-world conditions such as floodplains, where the interaction between the main channel and adjoining flood zones introduces complex flow dynamics. The primary objective of the study was to develop dimensionless relationships for the sequent depth ratio and relative energy loss during hydraulic jumps, both with and without accounting for a volume force (Fx), which models momentum transfer effects using an analogy to Borda-Carnot's formulation. The investigation aims to validate these relationships through controlled laboratory experiments. Three configurations of the width ratio between the main channel and floodplain were tested. The theoretical models were shown to be in strong agreement with experimental data, particularly when the volume force Fx was considered for width ratios above 0.5. The energy dissipation capacity of the compound channel was found to be superior to that of traditional rectangular channels - up to 6% more efficient on average. The models demonstrated high predictive accuracy, with relative errors as low as 4.83% for energy loss predictions. Undoubtedly, this study contributes valuable insight for the design and optimization of hydraulic structures where energy dissipation is critical, and highlights the practical advantages of using compound channels in engineering applications.

The existing literature, such as the works of Kissilev (1972), Slissky (1970) and Chanson (1994), provided a fundamental understanding of the operating conditions of the considered energy extinguishing structures. Modern computational and physical modelling has further refined the design of dissipation structures, focusing on aeration, jet breakup, and turbulent flow behaviour. Modern computational and physical modelling has further refined the design of dissipation structures, focusing on aeration, jet breakup, and turbulent flow behaviour.

Although substantial progress has been made in studying the processes of damping kinetic energy of water flow at spillways and designing spillway structures under standard operating conditions of hydroelectric power plants, several gaps persist in the context of: 1) Transitional and non-steady operating conditions during the construction phase, 2) Combined effects of high-velocity jets, inadequate downstream water levels, and structural constraints, 3) Empirical and analytical models for hydraulic jump prediction under compressed jet scenarios and variable boundary conditions, 4) Quantitative assessment of flow parameters such as velocity, Froude number, and energy levels at specific locations within the stilling basin.

The primary objective of this study is to conduct a comprehensive hydraulic assessment of Spillway No 2 at Boguchansky HPP during the construction period, focusing on: 1) Determining key flow parameters, such as flow depth, velocity, and hydraulic jump characteristics, in both free overflow and pressure discharge modes, 2) Evaluating the energy dissipation efficiency of the stilling basin under transitional flow regimes, 3) Assessing the jet trajectory and its implications for downstream erosion, 4) Proposing optimal design improvements to ensure structural safety and reliable energy dissipation during peak discharge events.

This article offers a pragmatic and context-specific solution to a common, yet underrepresented, engineering problem: managing transitional discharges in a spillway under construction-phase constraints. Its contributions include: 1) Deriving a quantified assessment of spillway behaviour under non-steady flow conditions, 2) Providing actionable design criteria for ensuring safe operation and minimal downstream impact, 3) Establishing a repeatable methodology applicable to other large hydropower projects facing similar transitional challenges. Furthermore, it enhances the understanding of hydraulic jump mechanics under hybrid flow regimes and supports engineering decisions through empirical validation and historical design references.

DESCRIPTION OF THE HYDRAULIC STRUCTURE

Geometric Characteristics of Spillway No 2

Initial data:

Longitudinal section of the spillway No 2 with combined variants designs for the period of the temporary exploitation of the hydrotechnical complex (Fig.1) (Guryev et al., 2023; Toloshinov et al., 2009).

The layout of Boguchansky Hydraulic Plant Constructions Presented in Fig. 2 (Guryev et al., 2020; 2021; 2023).

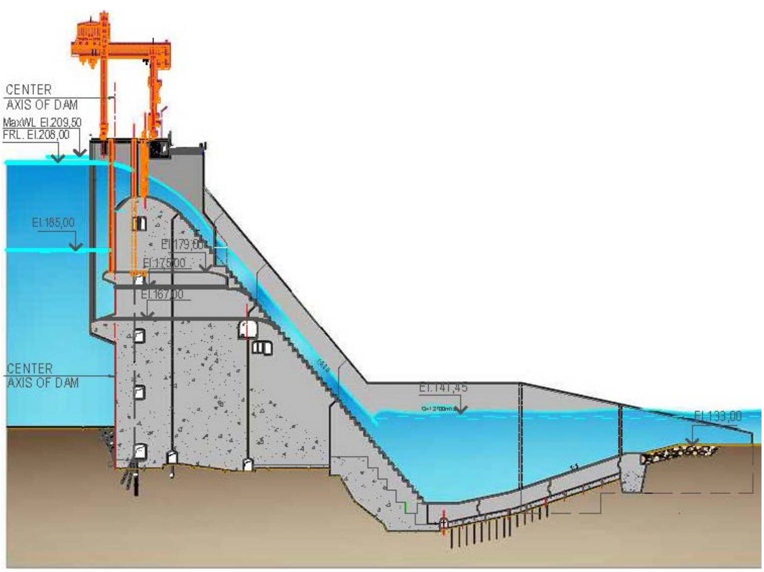

Figure 1: Longitudinal section of the spillway No 2 with combined variants designs for the period of the temporary exploitation of the hydrotechnical complex

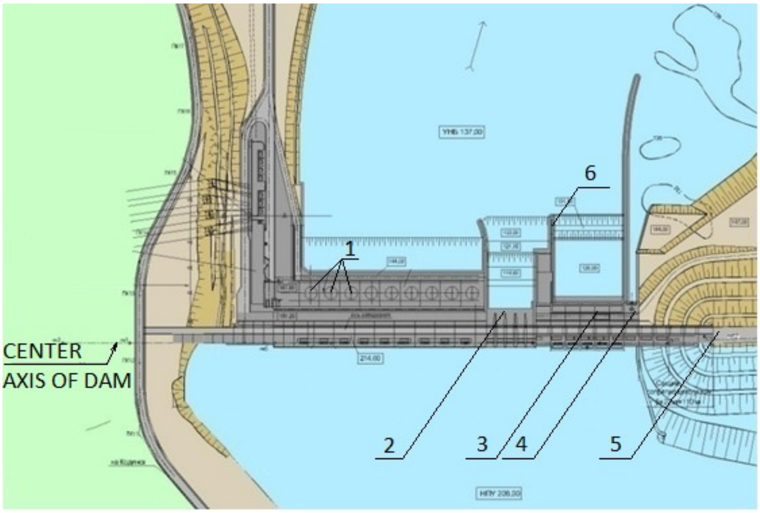

Figure 2: The layout of Boguchansky Hydraulic Plant Constructions:
1. Hydroelectric power station; 2. Surface spillway No 2 and 3. Deep spillway No 1 and 4. Timber transmission facility; 5. Ground dam; 6. Separate wall between spillways No 1 and 2

Operational Conditions during the Construction Phase

In the process of developing options for the passage of construction costs during the temporary operation of hydraulic works Boguchansky HPP It was considered an option with a spillway No 2 as the main spillway facility.

In this variant, the calculation of the spillway No 2 capacity was performed with free overflow through a flat threshold at the mark El. 167.0 m at the Full Reservoir Level (FRL) El. 175 m and water level forcing up to the Reservoir water level (RWL) El. 185.0 m. It was considered, among other things, the energy dissipation in the stilling basin.

The task of these calculations is determination of flow parameters in the stilling basin and in its outlet section.

THEORETICAL FRAMEWORK

The dependence of the initial data on the capacity of spillway No 1 is well described by the following equation (Guryev et al., 2023):

$$Q = 976.4\left(z_{RWL} - 150.1\right)^{0.487} \tag{1}$$

Taking into account fluctuations in the water levels in the downstream when the upstream level changes and the number of working culverts of spillways No 1 and No 2 and HPP units, the flow rate of one turbine can be described by the equation:

$$Q = 142.64 + 10.54\left(z_{RWL} - z_{TWL}\right) - 0.00632\left(z_{RWL} - z_{TWL}\right)^2 \quad (2)$$

Dependence of the depth of water in the downstream of the h_{TWL} on the flow rate

$$h_{TWL} = 0.03\,Q^{0.56} \quad (3)$$

The maximum flow rate of the hydro technical complex is $Q_{p = 0.2\%} = 11{,}700$ m^3/s, taking into account the transformation of the flood.

According to the conditions of the layout of the culverts of the spillway No 2, the maximum head is H = 18 m with a minimum threshold mark El.167.0 m. This pressure is crucial for the capacity of spillway No 2 and the assessment of the safety of its operation in the downstream.

For medium-sized working spans:

$$Q = 0.987 \times H^{-0.0021} \times 0.35 \times 10 \times \sqrt{2g}\,H^{3/2} = 15.3\,H^{1.4979} \quad (4)$$

For the end working spans:

$$Q = 0.968 \times H^{-0.0054} \times 0.35 \times 10 \times \sqrt{2g}\,H^{3/2} = 15.01\,H^{1.4946} \quad (5)$$

When the spillway works with the whole front, the throughput of 2 ...4 spans will be determined by the dependence (4), and the 1st and 5th spans by the dependence (5).

The sequence of opening the gates is as follows: 3-4-2-5-1. The maximum flow rate of the construction period is 5500 m^3/s can be skipped at a head El. 17.5 m, which at Reservoir water level (RWL) El. 185.0 m corresponds to the mark of the culvert threshold El. 167.5 m.

METHODOLOGY

Methods for studying the parameters of free-falling stream jets

The main purpose of studying the flow parameters at the stilling basin is to determine the depth and velocity of the flow at the outlet, which ultimately determine the degree of deformation of the riverbed in the lower reaches and its danger to the stability of the end part of the spillway (Lappo et al., 1988; Slissky, 1970; Kissilev, 1972; Chanson, 1994; Willey et al., 2010; Guryev et al., 2021; 2023; Caballero et al., 2021; Terrier et al., 2022),

Further calculations are performed for the conditions of skipping the maximum flow rate at the construction period 5,500 m^3/s.

At the average flow velocity V_o in the end section of the crest threshold, the jet trajectory is described by the following equation:

$$z = 9.81\frac{x^2}{V_o^2} \tag{6}$$

where:

x = Horizontal distance from the outlet section of the culvert; z = Vertical distance from the flow axis in the outlet section of the culvert to the axis of the flow section under consideration.

RESULTS AND DISCUSSION

The calculation of the parameters of free-falling jets allows you to assign the height of the side walls of the spillway, there is a need to increase the height of the side walls by 6 to 7 m, and the jet falls on the drain surface at a distance of 77 m from the centre axis of dam.

As can be seen from Figs. 3 and 4, in the spillway No 2 version with a pressure discharge, there is a need to increase the height of the side walls of the spillway towards the downstream at 9 to 10 m, i.e., 3 meters more than in the version with a free overflow of water.

Determination of the parameters of a hydraulic jump in the stilling basin

Fig. 3 shows the profile of the jet at the spillway No 2 for the construction period with a water well with a free overflow of water over the threshold. Fig. 4 shows the profile of the jet for the variant with energy dissipation in the stilling basin and a pressure outlet.

The parameters of the hydraulic jump are determined by the formulas of a flat hydraulic jump for a jet width of 10.0 m equal to the width of the water inlet of the culvert. In fact, the width of spans No 2...No 5 is 12.5 meters, and the width of span No 1 is 9.5 m. The acceptance of the calculated width of the in the stilling basin of 10 m instead of 12.5 m goes into reserve. The adoption of the width of the span No 1 equal to 10.0 m instead of 9.5 m is also justified, since the flow of the jet of the first span onto the left side wall will inevitably cause a decrease in the energy of the jet, which will be compensated by the adoption of the calculated width of the stilling basin 10.0 m for the span No 1.

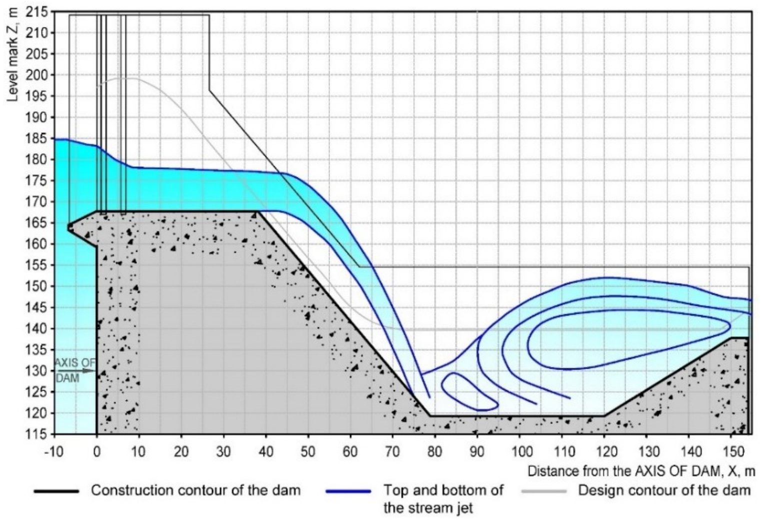

Figure 3: Longitudinal profile of spillway No 2 for the construction period with a stilling basin and with a free overflow of water over the threshold

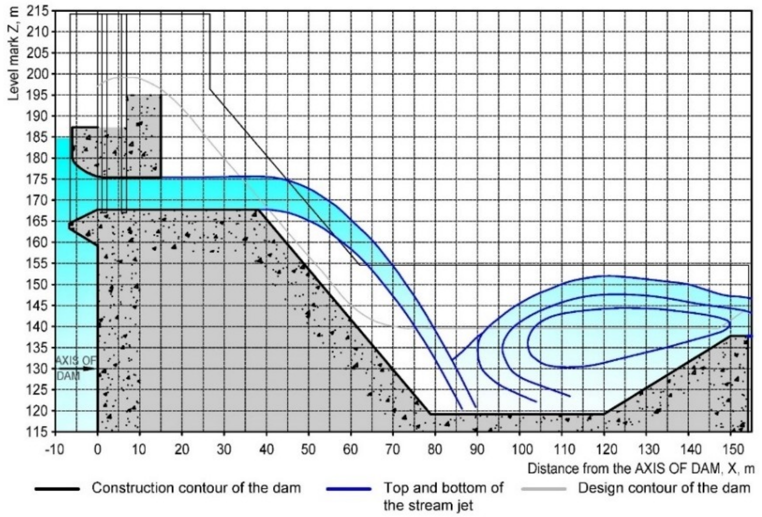

Figure 4: Longitudinal profile of spillway No 2 for the construction period with discharge under pressure and energy dissipation in the stilling basin

Calculations related to the determination of the parameters of the hydraulic jump are given in Table 1. As can be seen from Table 1, according to the parameters of the stilling basin, it is impossible to unambiguously conclude about the reliability of its operation when the during river discharges in the construction period.

Table 1: Determination of hydraulic jump parameters

Parameter	Calculated dependence	Dimension	Variant with free overflow	Pressure expiration variant
Compressed depth h_1		m	3.41	3.20
Velocity in compressed section V_{compr}	$V_{compr} = q/h_1$	m/s	32.24	34.43
The incident Froude number F_1 in the compressed section	$F_1 = \frac{V_{compr}^2}{gh_1}$	-	31.87	37.76
The jump's second conjugate depth h_2 (Belanger, 1828)	$h_2 = 0.5h_1\left(\sqrt{8F_1+1}-1\right)$	m	25.57	26.26
Specific consumption q	5500/69.5	m^2/s	79.14	79.14
Critical depth $h_{кр}$	$\sqrt[3]{1.05q^2/g}$	m	8.75	8.75
Critical velocity V_{cr}	q/h_{cr}	m/s	9.04	9.04
Energy level at the threshold Z_p	$137.5 + h_{cr} + 1.2V_{cr}^2/2g$	m	151.65	151.65
Energy in the well E_{well}	$Z_{threshold} - Z_{bottom}$	m	32.65	32.65
Depth of water in the well h_{well}	$E_{well} = h_{well} + \frac{1.4q^2}{h_{well}^2}$	m	32.22	32,22
Classical hydraulic jump length L_j^* (Kissilev, 1972)	$L_j^* = 2\frac{(\boldsymbol{h}_2-\boldsymbol{h}_1)^3}{\boldsymbol{h}_1\boldsymbol{h}_2}\times\frac{\left(10+\sqrt{F_1}\right)}{F_1}$	m	122.6	124.7

Fig. 5 shows the calculated picture of the operation of the stilling basin of spillway No 2. On the one hand, the depth in the culvert exceeds the second conjugate depth by 26% in the version with free overflow of water and by 22% in the version with pressure discharge of water.

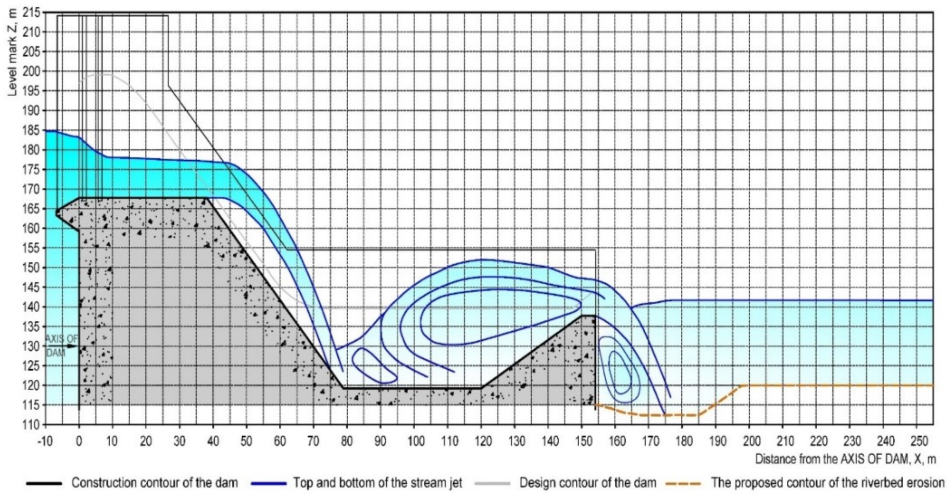

Figure 5: The longitudinal profile of the flow at the spillway No 2 with the damping of the and energy dissipation in the stilling basin with a free overflow of water during the construction period

But, on the other hand, the estimated length of the hydraulic jump is more than 120 meters, which is almost 4.3 times the length of the section with a possible maximum depth of 32 m and 1.7 times the total length of the stilling basin. At the same time, it should be taken into account that the end section of the stilling basin, made with the laying of 1:2.3 creates favourable conditions for the transit movement of the bottom jet without its vertical expansion. The consequence of such a hydraulic regime, ultimately, may be the removal of masses of water from the whirlpool zone above the transit jet into the downstream and the transition to the operation of the end section of the stilling basin as a springboard.

It follows from this that when determining washouts in the downstream behind the spillway No 2, it is necessary to consider the option of operating the stilling basin in the jet discharge mode.

Determination of jet parameters in the spillway No 2 for operation in the mode with flow discharge into the downstream

As noted above, when working with the spillway No 2 option, with a stilling basin, a mode may occur in which a threshold with an inclined frontal face will work as a springboard with a jet discharge from a stilling basin. The angle β of inclination to the horizon of the frontal face of the stilling basin threshold is 23.1° at the exit edge mark of 137.5 m.

To determine the parameters of the jet discarded by the springboard, it is necessary to determine its parameters at the descent from the edge of the springboard. The thickness of the jet on the edge of the springboard sock is found from the energy equation by taking the pressure distribution on the edge of the springboard sock according to the hydrostatic law. Denoting the energy in the compressed section of the flow through the E_{compr} and the energy on the edge of the toe - springboard through the E_{spr}, we will have the following energy equation:

$$E_{comp} = \varphi\left(z_{RWL} - z_{spr}\right) \tag{7}$$

$$E_{spr} = E_{comp} - h_1 - z_{spr} = h_{spr} + \frac{\alpha V_{spr}^2}{2g} \tag{8}$$

where E_{spr} = the energy of the flow on the edge of the springboard; E_{compr} = the energy of the flow in the compressed section of a free-falling jet; φ = coefficient accounting for the friction energy loss, the “impact” when the jet falls; for the free overflow mode, it can be taken, and for the pressure flow mode, it can be taken; h_i = energy losses along the length of the section from the place of the jet fall to the exit edge of the springboard; h_{spr} = the thickness of the jet on the edge of the springboard; α = Coriolis factor; Z_{spr} = 4.3 m – springboard height; V_{spr} = the flow rate at the edge of the springboard; g = 9.81 m/s^2 – acceleration of free fall.

The energy of the flow in the compressed section of the E_{comp} is equal to the sum of the velocity head and the thickness of the jet

The losses along the length of h_ℓ can be calculated using the dependence (9) for the flow parameters in the compressed section (Darcy-Weisbach, 1854).

$$h_\ell = \lambda \frac{\ell}{4R_h} \frac{V^2}{2g} \tag{9}$$

where R_h is the hydraulic radius

Determination of flow parameters in the outlet section of the stilling basin

The height of the fall flow at the threshold in the version of the spillway No 2 with a energy dissipation water threshold is quite large. Therefore, for it can be accepted expertly for the free overflow mode $\varphi \approx 0.93$, and for the pressure flow mode it can be accepted φ = 0.95.

The energy of the flow in the compressed section for the free flow option will be:

$$E_{comp.free} = 0.93 \times \left(185 - 119\right) = 61.68\, m$$

and for the pressure flow:

$$E_{comp.free} = 0.95 \times (185 - 119) = 62.7m$$

Calculations related to determining the parameters of the jet in the outlet section of the stilling basin in the case of its operation according to the jet discharge scheme are performed in tabular form and are shown in Table 2.

Calculations of jet drop range

The greatest distance of departure along the axis of the jet L at the level of the water level in the lower reaches can be determined by the dependence:

$$L = k_a \frac{V_{spr}^2 \cos\varphi_0}{g} \left(\sin\varphi_0 + \sqrt{\sin^2\varphi_0 + \frac{2gz}{V_1^2}} \right) \tag{10}$$

where k_a – coefficient depending on the aeration of the jet during flight; V_{spr} = the speed of descent of the jet from the toe-springboard; φ_0 = 23.1° = Angle of inclination of the jet to the horizon at the outlet of the stilling basin; φ_0 = 35° = Angle of the jet to the horizon at the descent from the toe-springboard; z = Excess of the centre of the jet above the water level in the diverting channel on the toe-springboard.

Table 2: Determination of the parameters of the jet descending from the threshold of the stilling basin

Parameter	Calculated dependence	Dimension	Variant with free overflow	Pressure expiration variant
Energy in the compressed section E_{compr}	$\varphi(z_{RWL} - z_{bottom})$	m	61.68	62.7
Compressed depth h_{compr}		m	2.78	2.75
Velocity in compressed section V_{compr}		m/s	31.65	32.0
Place of compressed section		m	77	80.5
The distance from the compressed section to the edge of the springboard	$157 - x_{compr}$	m	80	76,5
Hydraulic radius R_h	$\frac{hB}{2h+B}$	m	1.92	1.91

Darcy Coefficient λ	$\lambda = 0.11\sqrt[4]{\frac{\Delta}{4R}}$	–	0.014	0.014
Loss in length h_ℓ (Darcy-Weisbach, 1854)	$\lambda \frac{\ell}{4R_h}\frac{V_{spr}^2}{2g}$	m	7.44	7.31
The energy of the flow on the springboard E_{spr}	$E_{compr} - h_1 - z$	m	33.74	34.89
The depth of the flow on the springboard h_{spr}		m	3.90	3.82
The flow rate on the springboard V_{spr}		m/s	22.56	23.04
The Froude number of the flow at the descent from the toe – springboard	$F_{spr} = \frac{V_1^2 \boldsymbol{h}_{spr}}{g}$	—	13.3	14.2

Eq. (10) can be transformed into the following form:

$$L = k_a \frac{h_{spr} F_{spr} \sin\varphi_0}{z}\left(1+\sqrt{1+\frac{2g}{h_{spr} F_{spr} \sin^2\beta}}\right) \tag{11}$$

The aeration coefficient of the k_a flow is recommended to be taken equal to 1 at $F_{spr}<35$

To determine the height z of the location of the centre of gravity of the jet above the level of the downstream, it is necessary to know the dependence on the flow rate of the flow depth on the springboard sock.

The calculated flow rate of the construction period in the considered variant skipping of flow rate construction costs with a frequency of P = 0.2% is assumed to be equal to $Q_{\text{calc}=0.2\%}$ = 11,700 m^3/s.

According to formula (3), the flow rate Q = 11,700 m^3/s corresponds to the depth in the downstream h = 5.66 m at the downstream level of El. 141.16 m.

Given that the position of the centre of the jet on the edge of the toe – springboard is determined by the dependence 143.8 + h cos (β/2), finally we get the expression of the magnitude z:

$$Z = 143.8 + 0.41h_{scr} - 141.16 = 2.64 + 0.41\,h_{scr} \tag{12}$$

Taking into account the design of the end device of the spillway No 2 of the Boguchansky hydroelectric power station, and the parameters accepted for calculation, we have the following:

$$L = 0.47 F_{spr} h_{scr} \left[1 + \sqrt{1 + \frac{2\left(2.64 + 0.41 h_{scr}\right)}{0.329 h_{scr} F_{spr}}} \right] \tag{13}$$

For the inclined face of the threshold of a stilling basin with a ridge mark of 137.5 m, the dependence (13) takes the following form:

$$L = 0.36 F_{spr} h_{scr} \left[1 + \sqrt{1 + \frac{5.97}{F_{spr}}} \right] \tag{14}$$

The distance from the exit section of the springboard to the focus of the funnel riverbed erosion (the point with the maximum depth) is determined by the dependence:

$$L_1 = L + \frac{t - h_{dstr}}{tg\varphi_1} \tag{15}$$

where h_{dstr} = depth of the water in the downstream; φ_1 = angle of entry of the discarded jet into the water. In addition, the tangent of the angle of entry of the discarded jet into the water $tg\phi_1$ is determined by the following dependence:

$$tg\varphi_1 = \sqrt{tg^2\beta + \frac{2gz}{V_1^2 \cos^2\beta}} = 0.7\sqrt{1 + \frac{6.08\left(2.64 + 0.41 h_{scr}\right)}{h_{scr} F_{spr}}} \tag{16}$$

For the stilling basin with a flooded jet, you can take $tg\varphi = tg\beta = 0.427$.

As can be seen from the above calculations, the parameters of the jet largely depend on the level of the downstream, which is directly related to the operating conditions of spillway No 2.

Purely according to the hydraulic operating conditions of spillway No 2, it should be included in the work last of all when the Reservoir water level (RWL) = Full Reservoir Level (FRL) and the capacity of all other culverts and spillway structures of the hydrotechnical complex is exhausted. This condition is due to the fact that, all other things being equal, the minimum washouts of the riverbed of the lower reaches will be at its maximum levels, which is provided only if the spillway No 2 is turned on last.

Calculations of jet drop range after the inclined threshold of the stilling basin

Calculations related to the determination of the main parameters and the range of departure of the jet formed when the stream is thrown into the lower reaches by the inclined face of the threshold of the waterhole are performed in Table 3. These flow parameters are necessary to determine the parameters of the discarded jet and washouts of the riverbed of the downstream for the spillway option No 2 with of the stilling basin operating in the water flow waste mode.

Table 3: Calculations of the jet parameters during the discharge of the flow by the inclined face of the threshold of the stilling basin

Parameter	Calculated dependence	Dimension	Variant with free overflow	Pressure expiration variant
The depth of the flow on the springboard h_{spr}		m	3.90	3.82
The flow rate on the springboard V_{spr}		m/s	22.56	23.04
The Froude number of the flow at the descent from the toe – springboard	$F_{spr} = \frac{V_1^2 h_{spr}}{g}$	—	13.3	14.2
The distance of the jet departure along the axis, L		m	41.1	42.8
The tangent of the angle of entry of the jet into the water		—	0.427	0.427
The thickness of the jet at the entrance to the water	$h_{scr} + 0.17L$	m	10.88	11.18
The width of the jet at the entrance to the water	$B + 0.17LL$	**m**	**76.5**	76.8

CONCLUSION

This study delivers an in-depth hydraulic assessment of Spillway No 2 at the Boguchansky Hydroelectric Power Plant during its construction phase, under both free overflow and pressure discharge conditions. The evaluation was grounded in analytical modelling, empirical formulas, and theoretical fluid mechanics, aiming to ensure operational reliability and downstream safety under transitional flow regimes.

Key outcomes include the identification of critical design limitations in the current stilling basin configuration, particularly the inadequacy of energy dissipation under pressure discharge conditions. The analysis showed that the required hydraulic jump length exceeds the physical dimensions of the stilling basin, raising concerns about possible instability, especially under supercritical flow regimes. Moreover, the simulations revealed the potential for the stilling basin's end section to behave like a springboard, leading to jet discharge scenarios and increasing the risk of erosion in the downstream riverbed.

The results also underscored the need to raise the height of the sidewalls to contain high-velocity jets effectively, and provided a comprehensive set of parameters describing jet trajectories, flow depths, velocities, and Froude numbers under various configurations.

Ultimately, this paper contributes valuable insights into the transitional hydraulic behaviour of spillways under construction constraints, offering clear design recommendations to mitigate structural vulnerability and optimize flow control. The methodology and findings can be extended to similar hydropower installations worldwide, especially those confronting complex operating conditions during phased implementation.

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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