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HYDRODYNAMIC EFFECT ON THE ELEMENTS OF A DEEP STILLING BASIN

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ABSTRACT

The results of a study of the working conditions of downstream culverts of nature protection hydroelectric facilities and reclamation systems with a fairly deep but short stilling basin when various types of flow energy absorbers are installed on it are discussed in this article. The research aimed to analyze the change in the parameters of the hydrodynamic impact of the flow on individual elements of the downstream bracing to justify the optimal dimensions of the absorber, obtain the greatest effect of damping the excess energy of the flow and improve the work of the downstream with a uniform and uneven distribution of specific flow discharge, entering the basin.

As a result of an increase in the mixing length in the stilling basin and an increase in the disintegration of the jet into individual vortices behind the studied absorber, with an increase in flooding, the values of the pressure and velocity standards in the initial sections decrease, and the pulsation attenuation region decreases by approximately 1.5 times.

After entering the calculation complex, the resulting distribution fields of the averaged and pulsating pressure components across the whole interface section make it possible to evaluate the dynamic load on the bracing elements of the bottom of the basin and the discharge channel, as well as their stability.

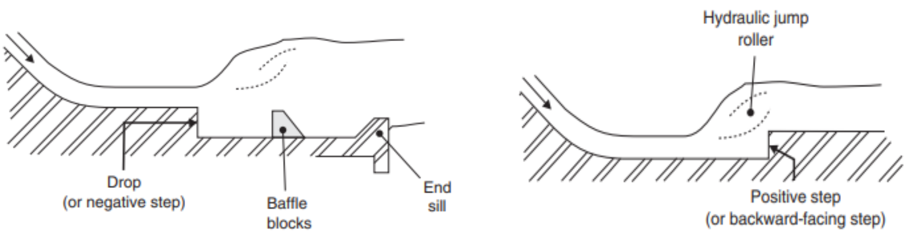
It is proposed to make the main part of the combined damper and the apron for a length of at least three depths of the quencher from monolithic reinforced concrete and to strengthen the rest with prefabricated slabs. As a result, it is possible to reduce the cost of arranging the interface section by approximately 24% while increasing the reliability of the operation of the outlet channels and the safety of spillways of environmental systems.

Keywords: hydrodynamic loads, deep shortened stilling basin, outlet channel.

INTRODUCTION

In connection with the urgent need for the reconstruction of hydraulic structures, the service life of which has long expired, during the repair, restoration after conservation of culverts of reclamation systems, in solving a number of other problems related to the safety of low-pressure hydraulic structures of the water management complex, the choice of the most reliable design of all elements of the culverts of the hydroelectric complex, since, according to various sources, approximately 37% to 44% of hydraulic structures suffered an accident due to the failure of the work of the spillway structure (Chernykh 2020, 2021; Rozanov and al., 1992; Chernykh and al., 1982, 1983; Rotmund, 1996; Vagabov, 1980; Morris Henri, 1969). The downstream transit tract of these hydraulic structures is most susceptible to the dynamic destructive effect of the discharged flow. To prevent the end part of the spillway from being washed away, approximately 90 years ago Pavlovsky (1937), and then Chertaousov(1962) noted the possibility of reducing the length of the stilling basin $l_к$ when placing a free hydraulic jump of length l_n in it, and it was recommended to take the length of the well within $l_к = (0,6...1)l_n$. Currently, there are a fairly large number of various kinds of relationships (Agroskin et al., 1964); Voynich-Syanozhentsky (1998), etc., which allow calculating the length and the depth of the water well, the size of which is reduced compared to the length of the perfect hydraulic jump. However, among a fairly large number of studies devoted to the possibility of reducing the length of the stilling basin against the size of a free jump, the question of taking into account the height of the threshold, which is implicitly related to the reaction of this obstacle, was raised only in a small number of works by Vagabov (1980), Rozanov (1979), Mikhalev (1955) and others. Over the course of a number of years, comprehensive studies of downstream devices in the form of a fairly deep, but short stilling basin, were carried out at the design stage of large hydroelectric facilities such as Zardezas (Algiers), Bhavani (India), Gumatskaya and Vartsikhskaya hydroelectric power stations (Georgia) (Volkov, 2012). Such designs require a detailed study of the hydraulic and hydrodynamic modes of operation (Chernykh et al., 1983). The schematic diagrams of the dams cited are shown in the appendix.

Any stilling basin must perform satisfactorily under various approach flow and tailwater characteristics. If the tailwater depth is too low, sweep-out results in a significant tailwater scour. Such poor flow must never occur under any flow scenario, because of large-scale scour in the tailwater. For all basins in which the tailwater depth is lower than 90% of the sequent depth of the classical hydraulic jump, the design should be verified in sufficiently large models (Chernykh et al., 2022). Damage to a stilling basin has to be countered under any circumstances given the implications for the safety of the entire dam. The tailwater depth-discharge relation has thus to be known before the selection of the stilling basin. Other aspects to be satisfied are cavitation and dynamic uplift resistance, scour control, and tailwater waves. Stilling basins expand behind outlets due to partial operation, or because of a width increase from the approach flow channel to the tailwater. In practice, abrupt expansion is of interest due to structural chute compactness. This design is considered here by Hager (1992) for gradually expanding basins. The basic features of stilling basins include drops, backward-facing steps (or sills), baffle block(s) and sudden expansion (Fig. 1). Hager (2021) reviewed the advantages of each type. Drops and backward-facing steps are simple elements used to stabilize the hydraulic jump. Drops (also called negative steps) are advised when the downstream tailwater level may vary significantly (Fig. 1a**).** Backward-facing steps (also called positive steps) are usually located near the toe of the jump (Fig. 1b**)** (Chanson 2004). Sudden expansion (in the stilling basin) is another technique to enhance turbulent energy dissipation and reduce the basin length.



a) b)

Figure 1: Sketch of the stilling basin

For several years, comprehensive studies of the downstream devices were conducted in the form of a fairly deep but short water-cutting well, making it possible to effectively extinguish excess flow energy, stabilize the formation of a hydraulic jump and deal with flow disruption, reducing the likelihood of downstream erosion for reclamation network structures. These studies were carried out on scale models at Moscow State University of Environmental Engineering (MGUP) under the leadership of N.P. Rozanov and I.S. Rumyantsev, and then at the Moscow Agricultural Academy named after K.A. Timiryazev (RGAU-MSHA) in the hydraulic laboratory of the department of hydraulic structures (Chernykh et al., 2017). The use of multiscale models of three-span culverts was caused by the need to combine the development of an innovative baffle with a correct assessment of the dynamic loads acting on the elements of the downstream fastening, with different schemes of spillway spans and the ability of the absorber to equalize the specific flow discharge both with a uniform and nonuniform approach of the flow to the energy dissipation site.

METHODS

Experiments on a rigid model (Fig. 2) were carried out at Reynolds numbers in the outlet channel varying in the range of [15000; 41700], Froude numbers Fr values in the compressed section have been varied from 4.472 to 10.954, depth *h* of the outlet trapezoidal channel has been varied between $0.29d_к$ and $0.65d_к$, where $d_к$ is the depth of the stilling basin, and the specific flow rates *q* were in the range 0.017 m^2/s to 0.042 m^2/s.

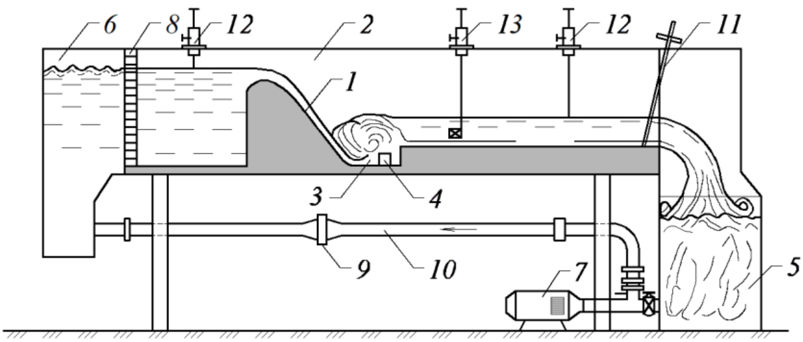


Figure 2: Scheme of a universal model installation: 1 - weir part; 2 – plexiglass walls; 3 - stilling basin; 4 - baffles; 5 - drain tank; 6 - pressure tank; 7 - pump; 8 – stabilizer grids; 9 – flow meter; 10 - supply pipe; 11 – downstream level regulator; 12 - Spitz scale; 13 – velocimeter

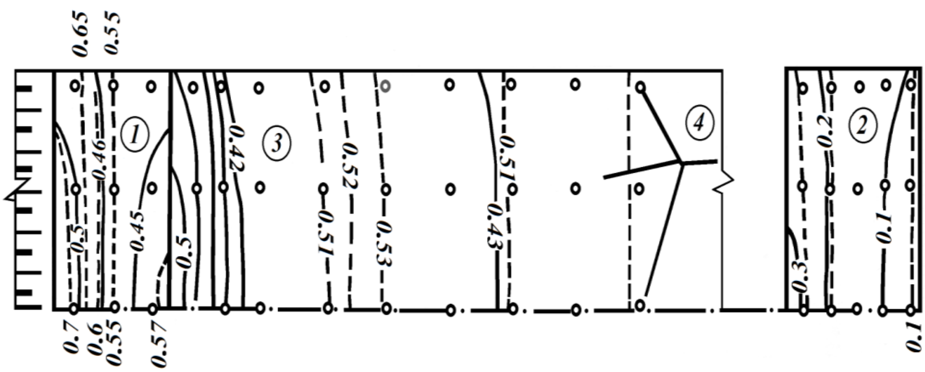
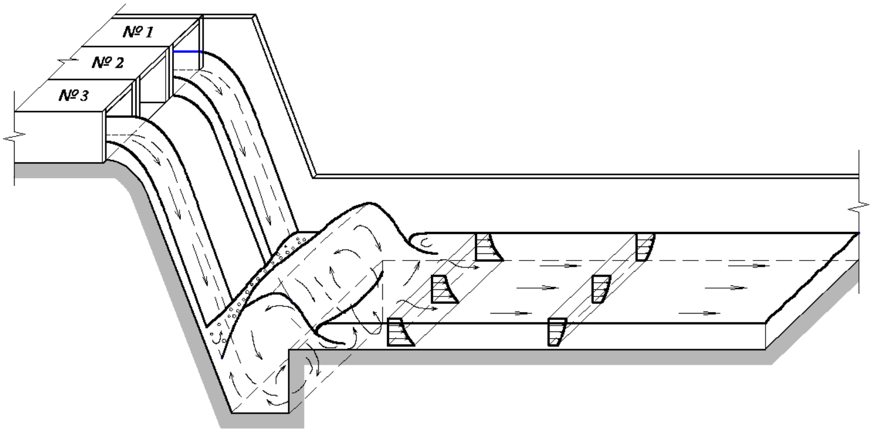


Figure 3: **The layout of the receiving elements of the piezometers and the distribution of the relative averaged pressure P/Z over the area of the tailwater attachment:** 1 - the bottom of the basin; 2 - water break ledge; 3 - interface area behind the well; 4 - receiving elements of piezometers; the solid line indicates isolines at $h/d_k = 0.4$, the dotted line – at $h/d_k = 0.65$

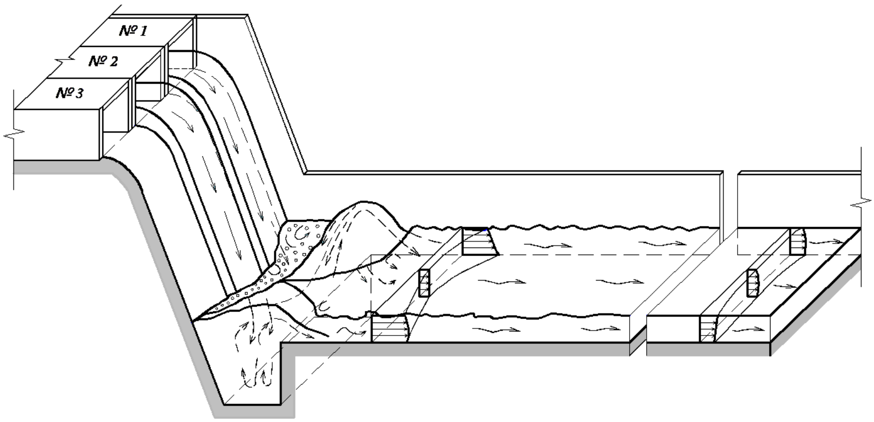
The study of hydraulics and hydrodynamics of the flow and the distribution of averaged and pulsating hydrodynamic pressures was carried out using a panel of piezometers, special tubes with a diameter of not more than 0.6 mm (Fig. 3) and inductive pressure sensors with a natural oscillation frequency of approximately 2 kHz with a receiving part diameter of 7 mm, which made it possible to implement almost all large-scale fluctuations and consider the measured values as pressure fluctuations at the point (Chernykh et al., 2022). The unevenness of the amplitude-frequency characteristics was less than 10%. As a result of processing realizations, when detecting fluctuations in water levels after recording impulse signals, the probability distribution law of fixed levels (*A*: pressure pulsation amplitude), flow pressure pulsation standard (*P′*) where $P^{'} = 2A/Z$ (Z is the total pressure on the structure; 2A - range amplitude of pressure pulsation and the average flow depth were determined. The average flow velocities (*V*) were measured by a microrotator, and the dynamic component of the velocities (*U′*) was measured by a cantilever-type strain gauge. When processing records, the standard deviation of pulsations *U′* and *P′* were determined under the assumption of a normal probability distribution law.

Initially, the downstream with a deep stilling basin of simple outlines N°2 (Fig. 4a) was investigated, in which several shortcomings were revealed: the formation of a secondary jump behind the well, increasing the length of the transition zone from 8 to 10 $l_к$; a rather complex nature of the distribution of hydrodynamic pressure in the interface area both in the well and in the zone of the secondary jump; strong fluctuation of the water surface in the discharge channel; uneven depths and velocities behind the well, especially noticeable when operating the gates of the culvert; and significant vertical and longitudinal pulsations of velocities and pressure (Fig. 4) (Chernykh et al., 2021).

The development of a surface whirlpool in most regimes indicated an insufficient damping capacity of such a well.



(a)



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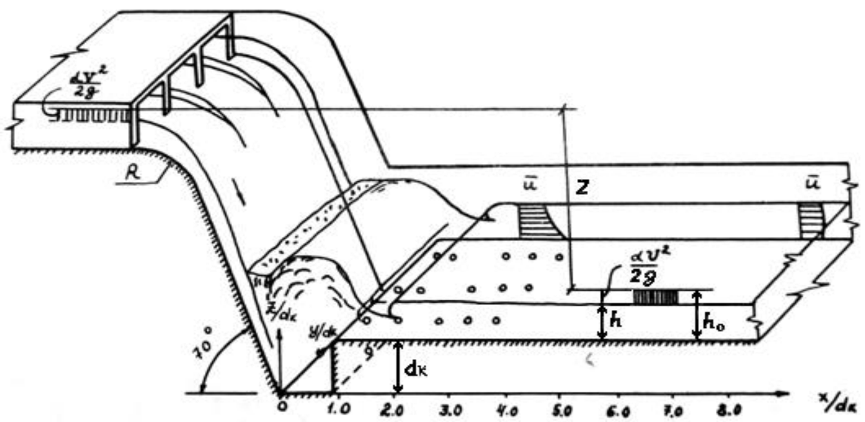

(c)

Figure 4: Examples of spreading schemes and diagrams of flow velocities for different operating modes of a structure with a deep well: a - the middle span of a three-point structure is closed; **b** - 2 adjacent spans are open (slotted dampers are conventionally not shown); **c**- flow during the installation of a deep stilling basin: circles indicate the installation locations of dynamic pressure sensors in the discharge section (sensors are not shown on the bottom and water-breaking ledge).

RESULTS AND DISCUSSION

As a result of the analysis of all possible conditions for the operation of the spillway with 20 design schemes of dampers (Fig. 5), the optimal variant of the combined damper with a slotted wall at the bottom of the end part of the short well (Fig. 5) was chosen at an angle of entry of the jet into the damper β_1=45° to 70°, which ensured the greatest effect of extinguishing energy (Chernykh 1982; Vagabor, 1980).

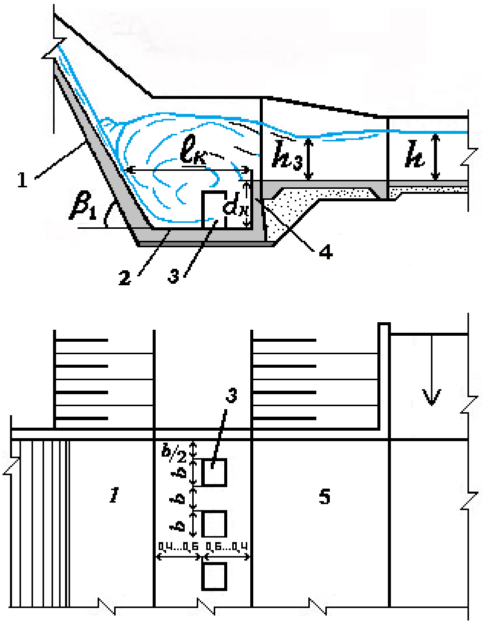

Figure 5: Scheme of a deep shortened stilling basin with a slotted wall at the bottom with a slope angle of the water slope β_1 = 50^0 ... 70^0: a - longitudinal section; **b** - plan; **1** – water slope with β_1 = 45^0…70^0; **2** - the bottom of the basin; **3** - slotted water-breaking wall; **4** - water-breaking ledge; **5** - apron

With such a combination of quenching devices, the pattern of water movement in the discharge channel changes dramatically compared to the base well without quenchers: the water levels are levelled; the wave vibrations on its surface are reduced; the drop sharply decreases (up to 1.59 h_3, that is, by approximately 44%), characterized by the ratio $(h_\kappa^{max}-d_\kappa)/h_3$, where h_κ is the water depth in the well, h_3 is the minimum conjugate depth behind the well; and the velocities decrease by 13.5%. Simultaneously, in many modes, there is no secondary jump behind the ledge. Only a slightly concave flow surface is observed.

In the front section of the well, limited by the water slope and the plane passing through the front face of the slotted structure, a flow is formed that is similar to the flow in the well without dampers. Here there is a vertically developed surface roller with a relatively high rotation velocity. A second roller is formed in the rear compartment, creating movement in the opposite direction. As a result, due to the collision of multidirectional jets, the bottom velocities behind the baffle decrease. Based on the experimental data, using the method of dimensional analysis, the following relationships were obtained that determine the optimal parameters of the combined baffle:

$$d_k = 2.53 h_{cr} \left(2 \log F_{r1} - 1.05\right) \quad \textbf{(1)}$$

$$l_k = 8.6 h_{cr} \left(F_{r1}\right)^{-0.36} \quad \textbf{(2)}$$

where $h_{cr} = \sqrt[3]{\frac{q^2}{g}}$ is the critical depth

$F_{r1}^2 = \frac{v^2}{gh_1} = \frac{q^2}{gh_1^3}$, where F_{r1} is the Froude number in the compressed section of the smooth water brake, located at the level of the discharge channel bottom with identical parameters of the hydraulic structure; h_1 and $v_1$are the depth and the velocity in the compressed section at $d_к = 0$, respectively, and $q = Q/b$ is the discharge per unit width b in the compressed section.

The formation of macroturbulent phenomena at the conjugation of the pools behind a smooth stilling basin led to the formation of an increased dynamic effect on the fastening elements from the flow side. The installation of a slotted wall at the bottom of the basin ensured minimal vertical emissions within its limits. Plots of averaged velocities in the discharge section in the flow with different schemes for maneuvering the gates of the structure are close to plots of smoothly changing motion. In this case, the pressure at the bottom is not distributed according to the hydrostatic law (Guryev et al 2015). In all studied ranges of Fr_1 numbers, the highest average pressures are concentrated at the beginning of the bottom of the stilling basin. Relatively sharply, the P values decrease at small values of F_{r1} and less intensively with an increase in the flow turbulence, respectively, at Fr_1 = 4.472 by 64.6% and at Fr_1 =10.954 by 30%. This occurs due to large eddies that arise as a result of the collision of the jet with the bottom. In this case, a surge of significant pulsations is also characteristic. As the jet moves away from the bottom of the basin, the values of both components of the hydrodynamic pressure decrease from the maximum for average pressures $P = 0.69Z$ (at the beginning of the attachment plate) and the pulsating pressure component $P' = 0.1Z$, reaching a minimum approximately in the center of the basin plate, Z - total head pressure on the environmental structure (Fig. 5). An increase in the values of P and P' (averaged and pulsed pressure) is typical for all schemes for operating spillway gates on a water-breaking ledge wherein the lower part of the vertical attachment, $P = 0.35Z$ and $P' = 0.067Z$. A sharp decrease in values is observed in the upper part of the threshold (approximately from 3 to 4 times). A partial increase in the amplitude *A* and the pressure fluctuation standard *P'* in the lower part of the ledge occurs due to the formation of a small bottom roller. The uneven distribution of loads, even when the structure is operating with all spans, leads to the fact that in the center of the well the loads are higher than at the sidewalls. Truly speaking, on the ledge, this was recorded only at its base.

Behind the water-breaking ledge, the values of *P* and *P'* decrease, so in the alignment $x/d_к$= 1.5/*P* = 0.18*Z* and *P'* = 0.044*Z*. Due to the intensification of the interaction of vortices carried out of the basin and formed in the secondary hydraulic jump behind the combined absorber. On the apron, the values of the pulsating pressure component rapidly decrease. Moreover, the length of pulsation attenuation compared to the process occurring after a perfect hydraulic jump of length l_n on a smooth water hole (at $d_к$ = 0) is approximately 1.5 times less (Fig. 6) (Chernykh, 1983).

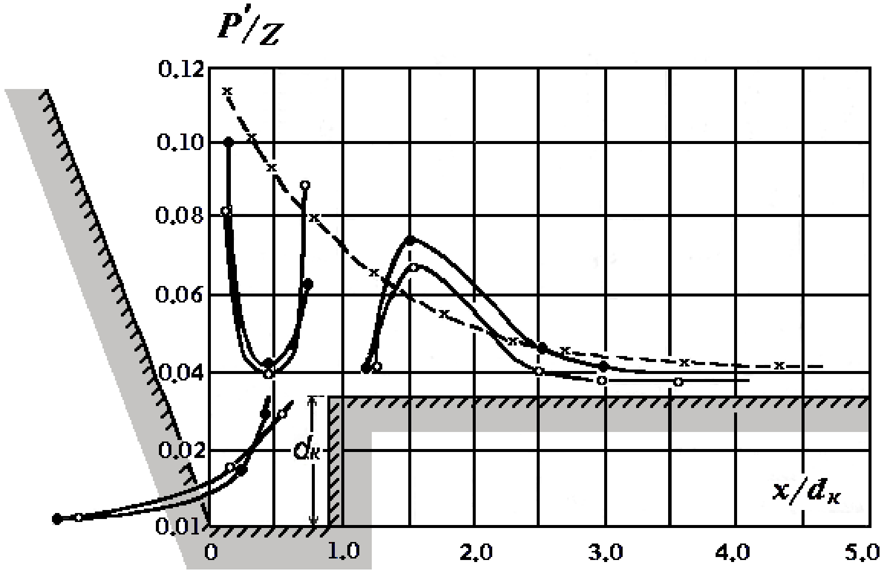

Figure 6: Pressure pulsation standards on the fastening elements for all operating spans of the culvert: 1 – h /dк = 0.4; 2 – h /dк = 0.65; 3 - on a smooth apron

With the flooding of the hydraulic jump that forms behind the combined basin, its extinguishing ability increases dramatically. With an increase in the depth in the outlet channel *h* from 0.4$d_к$ to 0.65$d_к$, the difference between the values of *P* on the axial and edge verticals decreases by 0.13*Z* at the beginning of the water well and by 0.017*Z* at its end, and the values of the pressure pulsation standard *P'* fall by 20%. At the same time, the planned uneven distribution of pressures and flow discharge is reduced.

When considering different schemes of operation of culvert spans, it was found that the strongest nonuniformity in the pattern of distribution of the pulsating component of pressure P' on the damper attachment elements and behind it is observed in the transverse and longitudinal flow directions with one extreme working outlet of the spillway (Fig. 7). In cross-sections, at the boundary of working pipes with closed holes, the largest ranges of pressure pulsations up to $0.7P$ are observed at the beginning of the water-breaking plate, but toward the ledge, their value can decrease to $0.15P$, and in the outlet channel at the end of the apron, it can decrease to 0.04. With an increase in flooding, the P' values in the initial sections decrease, and pulsation attenuation occurs in a shorter section (up to $1.8l_n$).

(a)

(b)

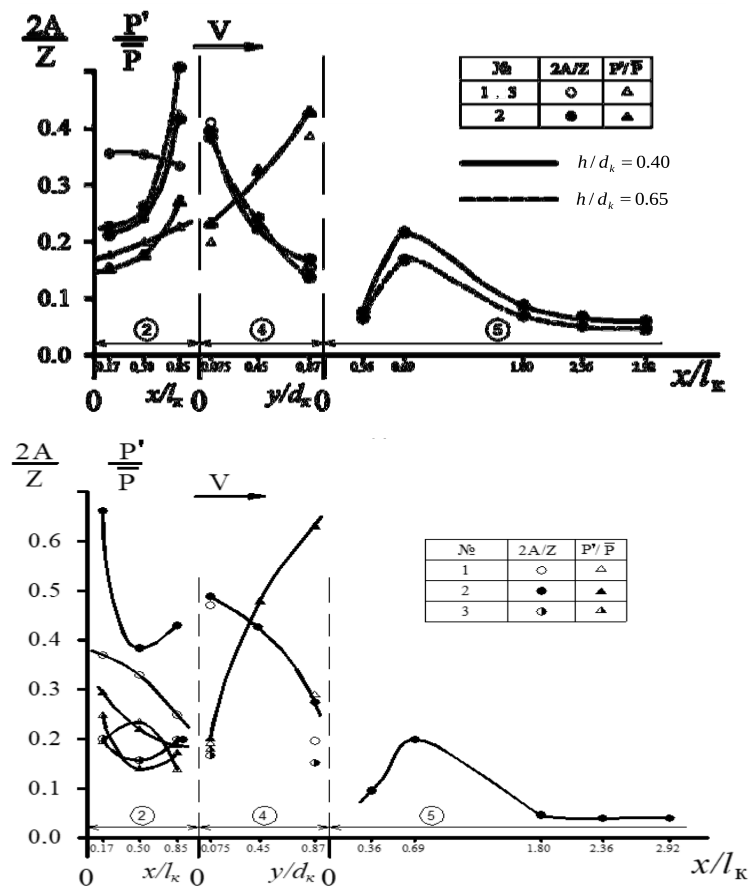

Figure 7: Distribution of the pulsating component of the pressure in the interface section when maneuvering the gates of the culvert: a - with symmetrical; b - asymmetrical opening of holes

Thus, the investigated type of combined well with a slotted wall at the bottom not only extinguishes energy 1.4 to 2.5 times more efficiently but also reduces the attenuation region of the pulsating component of pressure and velocities behind it by approximately 1.5 times. Preliminary estimates of the total hydrodynamic loads and calculations of the stability of individual elements of tailwater fastening according to existing methods for the quasi-static calculation of the elements of tailwater (Chernykh et al., 1983; Guryev et al., 2017; Guryev et al., 2021; Litvinov, 1982; Altunin et al., 2016; Wilfredo Zambrano, 1965; Suetina et al., 2020) allow us to recommend a deep stilling basin with a slotted wall at the bottom, a ledge and an apron for a length of at least $3d_к$ to be made of monolithic reinforced concrete, and the rest to be reinforced with prefabricated elements, including nonflat ones. This can lead to an average reduction of 24% in the cost of constructing an interface section in compliance with modern requirements for ensuring the safety of hydraulic structure reclamation and the reliability of channels of reclamation systems.

CONCLUSION

The compact dimensions of the combined deep stilling basin with a slotted wall at the bottom, which improve the conditions for pairing the pools with environmental structures, make it possible to recommend this organization of the water-cutting section as an effective means for damping the energy of the flow at low-pressure spillways, small bypass structures on roads and water outlets on the reclamation network. Revealed positive properties of the structure, the damping capacity of which increases sharply when flooding the hydraulic jump formed behind the ledge, in the range of Froude numbers such that $4.472 \leq F_r \leq 10.954$ in the basin.

The use of the obtained distribution patterns of the averaged and fluctuating pressure components on all elements of the conjugation section makes it possible to determine total hydrodynamic loads, assign fastening parameters and correctly assess their stability under the conditions of a spatial problem using known calculation methods. This, on average, by 24% can lead to a reduction in the cost of arranging the interface section while ensuring reliable and safe operation of the entire hydroelectric complex.

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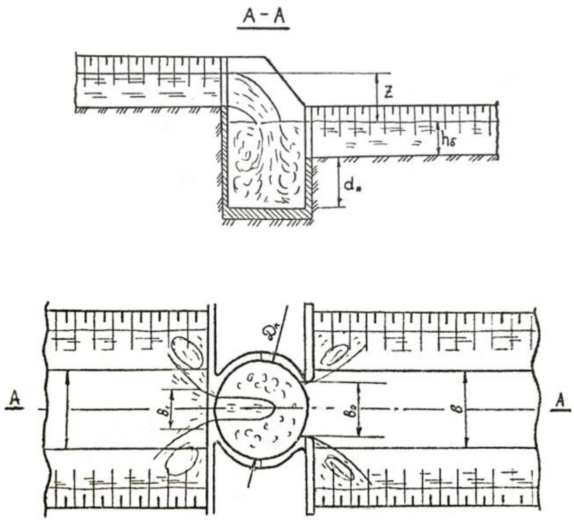
APPENDIX



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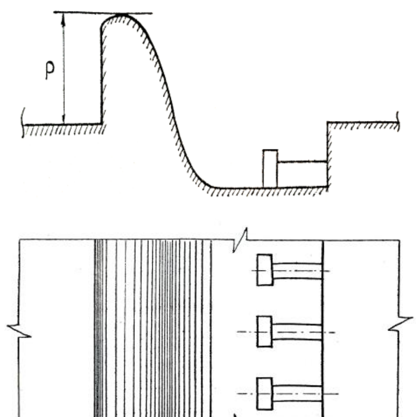

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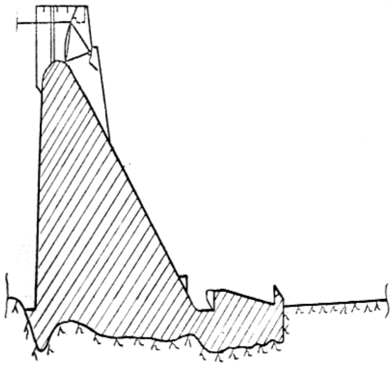

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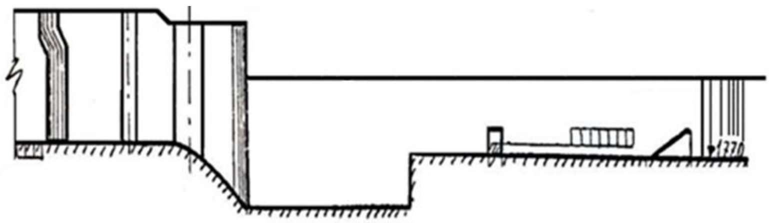

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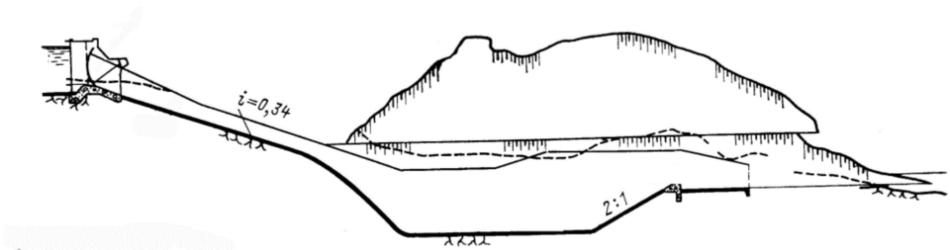

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Figure 8: Deep stilling basin downstream of dam spillways

a) Cylindrical stilling basin, proposed by the Mexican Society of Hydraulic Engineering
b) Bhawani Dams, India
c) Zardezas Dam, Algeria
d) Spillway of the Gomati I hydroelectric complex, Georgia
e) The main rapid flow of the Malpensa hydroelectric complex, Mexico.