



Optimization principles for inlet portal designs of gravity fish outlets of fish protection structures of water intake facilities*

Principios de optimización para diseños de portales de entrada de salidas de peces por gravedad de estructuras de protección de peces de instalaciones de toma de agua

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ABSTRACT

Prevention of juvenile fish from entering water intakes for various economic purposes utilizing a fish protection structure design is associated with the need to divert protected juvenile fish (fish outlet) to a safe place of a water source while maintaining its viability. The development of principles for selecting fish outlet structural elements is based on the existing hydraulic and biological requirements to ensure the effective movement of fish outside the influence of water intake. For the conditions of an open gravity fish outlet, the features of functioning and possible ways of its central element optimization are considered: the inlet part, the receiving section, and the transition section. Based on the analysis of the most characteristic features of the flow formation in the zone of the water intake influence, the conditions for the layout of the inlet part of the fish outlet are determined. The technical solution of the receiving section is based on the design features and calculation of the hydraulic parameters of the pressure nozzles. Moreover, the structural elements of the receiving section should be a sequential combination of nozzles from the functional aspect: a conical confuser – a cylindrical nozzle- conical diffuser, and the hydraulic conditions should correspond to biological requirements and ensure a flowing current that is safe for fish; the analysis of hydraulic and technical conditions of fish outlet is given. From the standpoint of modern hydraulic and biological requirements and the knowledge of fish behavior patterns, the optimal design is proposed for the design of the inlet portal of an open gravity fish outlet of the fish protection structure of the water intake facility.

Keywords: inlet chamber, protective screen, fish outlet, inlet area, receiving chute.

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RESUMEN

La prevención de que los peces juveniles ingresen a las tomas de agua para diversos fines económicos utilizando un diseño de estructura de protección de peces está asociada con la necesidad de desviar los peces juveniles protegidos (salida de peces) a un lugar seguro de una fuente de agua mientras se mantiene su viabilidad. El desarrollo de principios para seleccionar elementos estructurales de salida de peces se basa en los requisitos hidráulicos y biológicos existentes para garantizar el movimiento efectivo de peces fuera de la influencia de la toma de agua. Para las condiciones de un desagüe de gravedad abierto, se consideran las características de funcionamiento y las posibles formas de optimización de su elemento central: la parte de entrada, la sección de recepción y la sección de transición. Con base en el análisis de los rasgos más característicos de la formación de flujo en la zona de influencia de la toma de agua, se determinan las condiciones para el diseño de la parte de entrada de la salida de peces. La solución técnica de la sección receptora se basa en las características de diseño y cálculo de los parámetros hidráulicos de las boquillas de presión. Además, los elementos estructurales de la sección receptora deben ser una combinación secuencial de boquillas desde el punto de vista funcional: un confusor cónico - una boquilla cilíndrica - difusor cónico, y las condiciones hidráulicas deben corresponder a los requisitos biológicos y garantizar un flujo de corriente que sea seguro para pez; es dado el análisis de las condiciones hidráulicas y técnicas de la salida del pez. Desde el punto de vista de los requisitos hidráulicos y biológicos modernos y el conocimiento de los patrones de comportamiento de los peces, se propone el diseño óptimo para el diseño del portal de entrada de una salida de peces abierta por gravedad de la estructura de protección de peces de la instalación de toma de agua.

Palabras clave: cámara de entrada, pantalla protectora, salida de peces, área de entrada, tolva receptora.

1. INTRODUCTION

The preservation of water source ecosystems, including ichthyofauna, under the conditions of an ever-increasing anthropogenic load, manifested by water consumption increase, is one of the acute problems of our time. Prevention of juvenile fish into water intakes by means of a fish protection structure is associated with the need to divert protected juvenile fish (fish outlet) to a safe place while maintaining its viability. Generally, a fish protection structure's fish outlet is a complex of devices and elements, including an inlet portal; a fish-diverting tract (channel, chute); an outlet portal. If a section with a large terrain slope occurs on the route of a fish-diverting tract, then a connecting structure is provided (Xiao et al., 2019).

The existing layout and design solutions for fish-diverting systems are currently based on the use of fish behavior peculiarities and patterns (Pavlov & Pakhorukov, 1983), as well as on domestic and foreign experience concerning the design and operation of fish-diverting systems (Mikheev et al., 1997; Mikheev & Perelygin, 2007; Mikheev & Perelygin, 2014; Larinier & Travade, 1999; Burgi et al., 2006). At the same time, the variety of biological, hydraulic, technical, layout features and conditions significantly impact the successful solution of fish moving problems to a safe place of a water source. It should be noted that the nature of the fish outlet flow movement within the inlet portal in the area between the protective screen (mesh, blinds, drums, etc.) and the fish-diverting tract is generally the main criterion while developing a fish outlet structure. At the same time, the layout solution, the design of the elements, the conditions for conjugation of the bottom (horizontal or a sloped one), flow characteristics within the inlet portal must meet the fish safety requirements. In this regard, the development of principles for the selection of structural elements of fish diverters (outlets) based on existing hydraulic and biological approaches and requirements, will allow to avoid errors in their design, and fish diversion losses (Fang et al., 2020).

2. MATERIALS AND METHODS

To develop the main directions in design optimization for the inlet portal of the fish outlet, the principle of operation, functional features and possible ways of its constituent element optimization are considered. Subsequent analysis is limited only by the design of the inlet portals of open gravity fish outlets.

Inlet part. The entrance is the most functionally significant element, which provides the efficiency of protected fish diversion due to the properties of suction and involvement of juvenile fish with the flow. In open flows, the suction (vacuum) effect is manifested under certain conditions in the zones of flow separation and in whirlpool currents.

Receiving section. As a rule, the receiving section in the flow dividing unit occupies an intermediate position and, when analyzed the flow under rarefaction conditions, it can be considered between the conventional open water intake scheme and the nozzle scheme, therefore this section should have the smallest possible width.

Transitional section. The movement of fish along the channels (galleries and pipes) is dangerous for them, especially in the transitional (initial) section of the conjugation with the fish diversion tract, since the likelihood of injury from walls, protrusions, etc. is high, which increases with the length and number of local resistance rising, therefore, the hydraulic conditions and the length of the fish outlets should be optimal.

3. RESULTS AND DISCUSSION

Assessment of conditions in the influence zone of the inlet portal of fish outlet.

Water intake into the fish outlet should be considered as a damless water intake, since water is drained by gravity from the inlet chamber of the fish protection structure to the fish outlet. The lateral water outlet makes significant changes to the flow movement regime.

If during the design of water intakes, the main task is to combat sediment, then the main task for a fish outlet is to ensure the safety of fish diversion. The danger for fish is represented by increased turbulence (large gradients of transverse velocities, pulsations), the presence of separated flow currents with the formation of circulation zones, intense transverse circulation, etc. Accordingly, a laminar (smooth) velocity profile for fish is always preferable to a turbulent one. The entrapment of sediments is also an undesirable phenomenon, since their deposition in the channel of the fish diverting tract will change its cross-section, flow characteristics and regime.

Based on these positions, the characteristic features of the flow current formation in the influence zone of water intake are considered. Figure 1 shows the character of a flat flow with the options for water intake at a right angle to the coastline and along the approaching flow front (Chugaev, 1978).

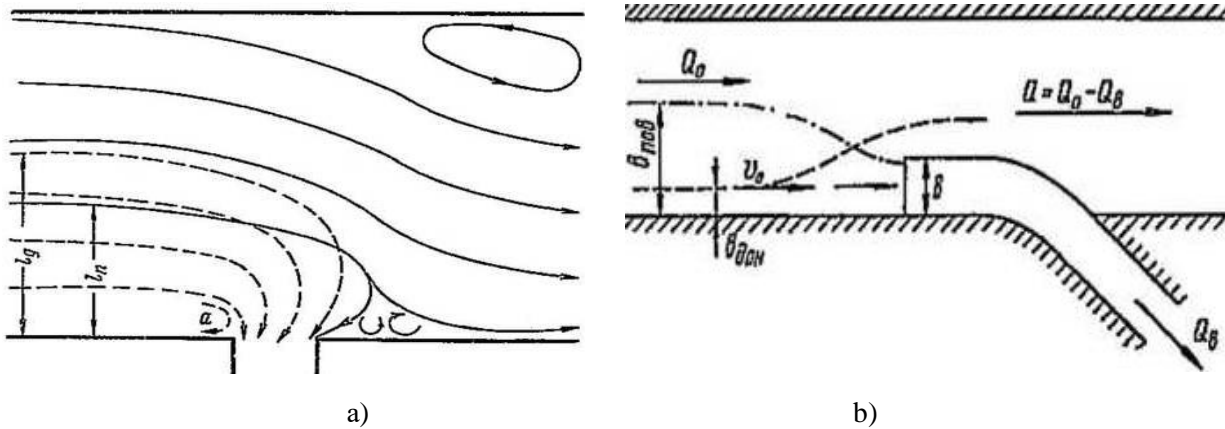


Figure 1. The flow current scheme at water intake from a water source
a – at lateral outlet; b – at front intake

With a lateral outlet (see Figure 1, a), before entering the water intake at point a, a vortex with a vertical axis is created in front of the water intake inlet face. The bottom lines of currents (dashed lines) are pulled into this low pressure zone, which involve bottom sediments, and, consequently, benthic fish, into the water intake.

According to V.A. Shaumyan, the zone of bottom jet capture l_n is larger than the zone of surface jet capture l_g , their values are determined by the following formulas

$$l_n = 1,17(k + 0,4)b; \quad l_g = 0,73(k + 0,05)b, \quad (1)$$

where b – the outlet width; $k = q_{outlet}/q_{river}$.

It is known that the width of the capture zone of bottom jets significantly exceeds the width of the capture zone of surface jets (without taking into account the river width, depth, the share of discharge diversion, etc.). The attempts to reduce the capture of bottom sediments by the means of a threshold setting at the entrance to the water intake are ineffective, and in fish diversion, the setting of thresholds is not permissible, since this will impede the passage of benthic fish species. With a wide front of the water intake, the axis of the vortex moves to the water intake, forming a circulating flow here.

At frontal water intake (Figure 1, b) the capture from the bottom layers of the flow is minimized.

The width of the capture zone of the bottom layers of the flow (b_{bot}) at the frontal water intake can be determined approximately by the following formula (\circ): $b_{bot} = 2(k - 0,5)b$, where $k = q_{out}/q_{river}$, thus, at $k \leq 0,5$ the capture of the flow into the outlet from the bottom layers is excluded $b_{bot} = 0$.

To increase the pressure a short water-capturing spur is installed in front of the water intake (Figure 2), due to which the water level in the river before the entrance to the water intake rises by 0.5-0.6 from the velocity head $v^2/2g$, where v – the average flow velocity of the river near the water intake.

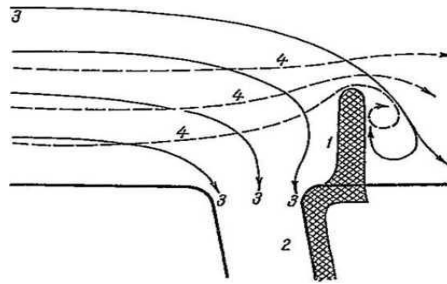


Figure 2. Short water intake spur (Hämmerling et al., 2022)
 1 – spur; 2 – water intake; 3 – surface jets; 4 – bottom jets

Based on the recommendations for the design of water intakes, an obvious conclusion is made that the frontal type of water intake is preferable for designing the inlet portal of the fish outlet, since it provides uniform intake (capture) of juvenile fish in depth. Besides, the frontal type of water intake fits harmoniously into the design of the fish protection structure with a protective screen installed at an acute angle to the flow, being a natural continuation of the screen - a kind of fish trap.

The design of the receiving section of the inlet portal of the fish outlet.

A flat jet flowing from a reservoir into a narrow chute is compressed in the horizontal plane. The degree of its compression in depth will not be the same - the jet is compressed more on the surface (in the vacuum-free zone) than at depth (Schlichting, 1969). Based on this, to optimize the receiving section, we will use the principle of comparing the hydraulic operating conditions of the inlet portal of the fish outlet with the hydraulic conditions of the nozzles, while the evaluation criterion of the nozzle design will be flow characteristics that is safe for fish, ideally a non-vortex (laminar) flow.

As it is known, external nozzles are divided into three main groups: cylindrical, conical (diverging and converging) and conoidal - with the edges rounded in the form of jet compression (Chugaev, 1978; Patrashev, 1953). The flow characteristics within the nozzle includes two independent parts: the central (axial), where the fluid particles move only forward, and the coaxial, in which the fluid particles are circulated. The minimum area of the free cross-section of the forward flow in the central part is called the compressed cross-section.

A vacuum is formed at the inlet part of the nozzle, which somewhat expands the compressed section and causes the flow discharge increase through the nozzle (in comparison with the thin wall hole), the flow coefficient $\mu = 0.82$. With the nozzles longer than 40-50 diameters, the suction effect does not compensate for the increasing hydraulic losses along the nozzle length.

Conical converging nozzles (used in hydraulic turbine nozzles, jet monitors, etc.) are capable of providing smooth, almost irrotational flow acceleration up to the maximum speed in the compressed section (throat). The jet leaving the converging nozzle has a high specific kinetic energy and outlet velocity (due to the small value of hydraulic resistance), which makes it possible to use them for fish capture. The discharge coefficient reaches its highest value $\mu = 0.946$ at the angle equal to $13^{\circ}24' \approx 13,5^{\circ}$ (Chugaev, 1978; Patrashev, 1953).

Conical converging nozzles are capable of providing a smooth, almost irrotational acceleration of the flow up to the critical (for fish) velocity in the throat (which is assigned in accordance with the SP requirements) (SP101.1333.2012 Retaining walls, 2020).

In conical diverging nozzles, the fluid jet velocity in the compressed section is greater than the jet velocity at the nozzle outlet, and the pressure, on the contrary, is less, since there is a vacuum in the compressed

section of the nozzle. The vacuum in the diverging nozzle is greater than the vacuum in the outer cylindrical nozzle and it grows with the taper angle increase, which should be sufficiently small $\theta = 5-7^\circ$. The flow discharge through such a nozzle is much higher than the flow through the external nozzle, and the output speeds are much lower. It should be noted here that the expansion of the channel is a fact of salvation for fish in a narrow space, since it reduces the likelihood of injury due to the free area increase. Therefore, it is better to use a smoothly expanding chute to divert the fish from the throat.

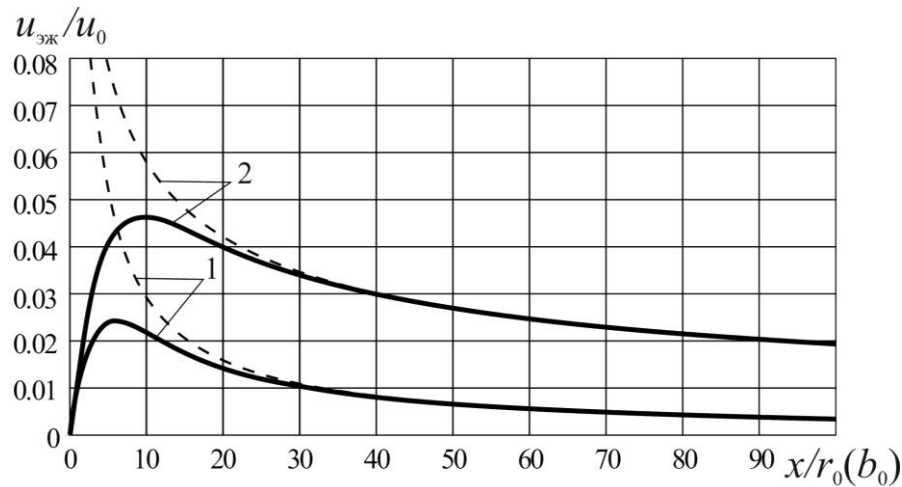
The conoidal nozzle is outlined by the jet shape flowing out of the hole: the inlet part is made along a complex surface of double curvature, and the outlet part has a cylindrical shape, which eliminates the disadvantage of the conical converging nozzle consisting in the compression of the liquid jet when it leaves the nozzle, that is, the compression ratio is equal to one in the conoidal nozzle. Therefore, the velocity and flow discharge coefficients for this nozzle are approximately equal to each other $\mu = \varphi = 0.97-0.99$ (depending on the pressure and the quality of the nozzle inner surface processing).

Thus, the basis for the optimization of the layout and design of the inlet portal of the fish outlet is based on the features of nozzle operation with axial symmetry, in which fish safe conditions can be created by the following combination of nozzles:

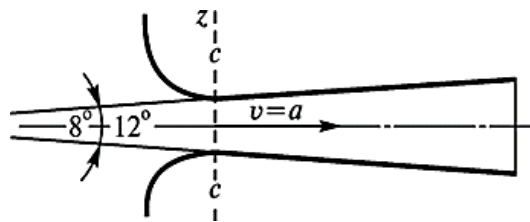
- at the inlet (to increase the capturing and suction capacity) - conical confuser or conoidal (to increase the throughput of the fish outlet);
- in a compressed section (throat) - a cylindrical nozzle;
- at the outlet (for a smooth and safe diversion of fish) - a conical diffuser.

However, when considering flat jet flows, it is necessary to take into account their distinctive features from axisymmetric ones, which consist, first of all, in the intensity of the jet expansion, which, in turn, affects the ejection ability of jets. For comparison, Figure 3 shows the graphical patterns of changes in the relative velocity of ejection along the length x for round (nozzle radius r_0) and flat (hole width b_0) jets in the form of the ratio of the average jet velocity (u_0) in the section and the rate of fluid inflow from the surrounding area to the outer boundary (u_{ej}) (Mikheev & Borovskoy, 2015).

Obviously, the ejection capacity of a flat jet is much higher than that of an axisymmetric jet, the maximum ejection velocity falls approximately in the middle of the initial section. In contrast to the axisymmetric jet, the peak of the flat curved jet is shifted to the right and the maximum ejection velocity falls on the second half of the initial section. It is important to emphasize that a flat jet, limited by the walls of the fish diverting chute, is capable of creating a much greater vacuum than a round one, and, therefore, it expands much more in the diffuser channel of the fish outlet.



a)



b)

Figure 3. Conformity to the combined nozzle shape to the ejection ability of the submerged jet (Mikheev & Borovskoy, 2015). a - the graph of the ejection velocity changes along the length of the circular (1) and flat (2) hyperboloid jet; b - combined nozzle

As can be seen on Figure 3, the ejection ability of the submerged jet corresponds to the combined nozzle shape.

Estimation of the flow characteristics in the inlet portal sections.

An important factor influencing the conditions of fish outlet is the flow characteristics, namely, the degree of turbulence, which is assessed by the Reynolds criterion. It indirectly characterizes the flow safety for fish. The results of Reynolds and Gibson's experiments show (Patrashev, 1953; Prandtl, 2000) that the value of Re_r is significantly influenced by the sign of the longitudinal velocity gradient, which is not the same in the nozzles. In confuser flows, in which the downstream velocity increases and, therefore, the velocity gradient is positive, the critical Reynolds numbers are significantly more than 10 times higher than those indicated for cylindrical pipes, and they are the larger, the greater the taper angle (confusion angle) is. This testifies to the laminarization of the flow in the confuser nozzles. On the contrary, in diffusers, in which the downstream velocity decreases and, therefore, the named gradient is negative, the critical Reynolds numbers are much lower than for cylindrical sections. This is well illustrated by Gibson's experiments, in which a laminar regime was simultaneously observed in the confuser part of the flow, and turbulent regime - in the diffuser part.

Experience in the development of highly efficient nozzles, including supersonic nozzles (Laval, Stentan, Frankl, etc.) (Samoilovich, 1990), indicates the need to maintain a smooth sequential conjunction of all elements of this sequence, in particular for fish outlet conditions, these are the inlet chamber + confusor; confusor + cylinder; cylinder + diffuser; diffuser + conoidal outlet channel (tract).

Such nozzles are known and used to increase the throughput both for liquids (for water turbines, pumps, etc.) and for gases to overcome the critical speed in steam, aircraft turbines, rocket engines, etc. Laval's nozzle is a gas channel with a special profile (with a narrowing) to change the gas flow velocity passing through it (Prandtl, 2000; Samoilovich, 1990). In the simplest case, Laval's nozzle can consist of a pair of truncated cones conjugated with narrow ends. Both versions have a lot in common - there are all elements (confusor, cylinder, diffuser) smoothly merging into each other.

When designing a fish outlet, it is necessary to strive for the smallest possible change in the upstream flow regime (inlet chamber) and to the water velocity decrease before the fish outlet. If the location of the water intake and flushing openings in the upstream flow is unsuccessful, there is a threat of sediments when approaching the water intake opening. In this case, the flow can be largely displaced from the water intake openings in the approach section by deposited sediments, which is naturally undesirable (Figure 4, a) (Chugaev, 1978).

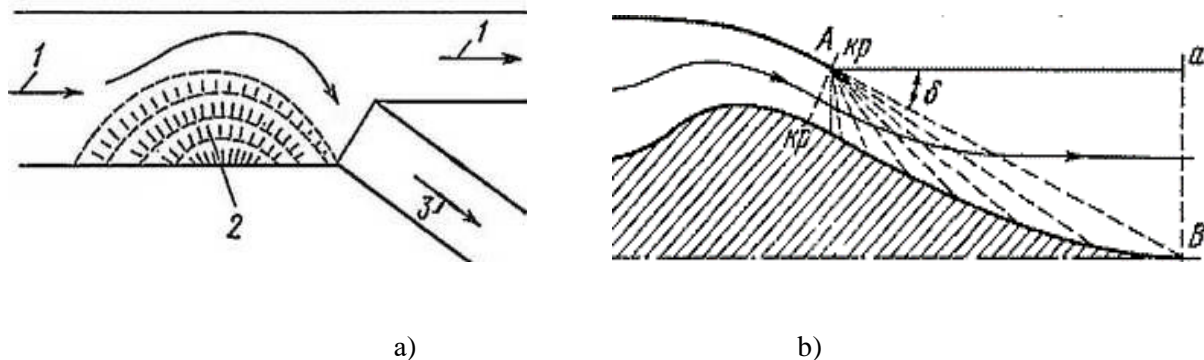


Figure 4. Substantiation of the inlet part shape of the fish outlet.
a – sedimentation in front of the entrance water intake opening;
b – an adjustable nozzle diagram with a central body;
 1 - river; 2 - sediment deposition area; 3 - water intake into the channel

The reference point for designing the inlet part of the fish outlet is a nozzle with a central body to regulate the flow discharge, a schematic diagram of which is shown on Figure 4, b (Prandtl, 2000; Loytsyansky, 2003). In such a nozzle, the gas flows through a coaxial channel (between the central body and the shell); the critical section can be regulated by the longitudinal movement of the central body. The flow at the outlet turns to the axis of symmetry, which in the receiving section design corresponds to the flow bending towards the fish outlet and is an advantage of this design.

The profile of the central body is selected in such a way that at the reduction point of any characteristics, the direction of the flow behind it coincides with the direction of the wall, the critical section and the angular point of the flow are located on the shell cut. In this case, the gas expansion is one-sided, and the critical section is inclined to the axis by the angle δ equal to the gas flow rotation angle around the point A. The shell must be parallel to the wall of the central body in the critical section of the nozzle. This leads to additional frontal resistance due to the losses on the external flow around the shell converging part. If the calculated values of the Mach number ($Ma \leq 2$) are large, the central body can be made conical. In the case of a flat nozzle, the contour of the central body is the streamline of the Prandtl-Mayer flow (near a

convex angle) with a flat sonic line (Prandtl, 2000). The contour of the axisymmetric central body is close to the flat flow streamline. For fish diversion conditions, the advantage of this nozzle is that it matches the shape of the combined nozzle and ensures smooth rotation for fish diversion.

The angle of flow diversion plays a significant role in the flow characteristics within the fish outlet. Taking the flow diversion angle of the water intake, they strive to obtain, possibly, a smoother conjugation of the channel with the river, otherwise, if there are sufficiently high velocities in the river, the likelihood of extensive whirlpool zone occurrence, lateral compression of the flow, uneven inflow and water discharge reduction increases.

For damless side water intakes, the angle of flow diversion is assigned within the range $\alpha_{po} = 35-75^\circ$, large angles (up to 90°) are taken under appropriate topographic conditions and relatively low water flow discharge intakes, and the design of water intakes becomes much more complicated at the angles less than 35° (Chugaev, 1978). With regard to the conditions of fish diversion they evaluate, first of all, the transverse circulation of the flow arising at the turn and affecting the distribution of juvenile fish in the cross section. In the course of studying the inlet portals of fish-passage-spawning channels (Dragunova et al., 2020), it was found that the optimal angle for fish attraction is $\alpha_{po} \approx 36^\circ$, at which the transverse circulation covers the entire cross-section in the flow attracting fish.

In real conditions, the angle of diversion is taken by taking into account the general layout of the water intake facilities, the terrain, the location of the outlet portal in the downstream as the part of the structure node (relative to the RZS, the dam section), the tract length, etc.

The performed complex analysis made it possible to propose a schematic diagram of the arrangement of the main elements (Figure 5) of the fish outlet suction head capable of providing optimal conditions for the safe diversion of fish (Borovskoy & Temovoy, 2021).

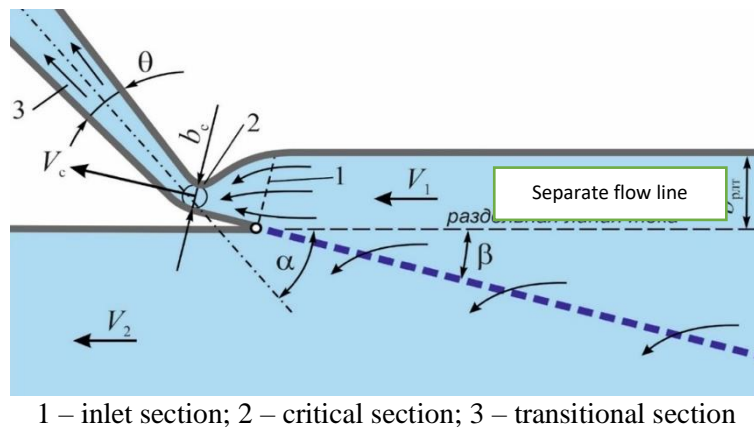


Figure 5. Schematic layout diagram of the inlet portal main elements of open fish outlet

On the basis of the analysis, a diagram of the layout-constructive solution of the inlet portal of an open gravity fish outlet is proposed (Figure 6),

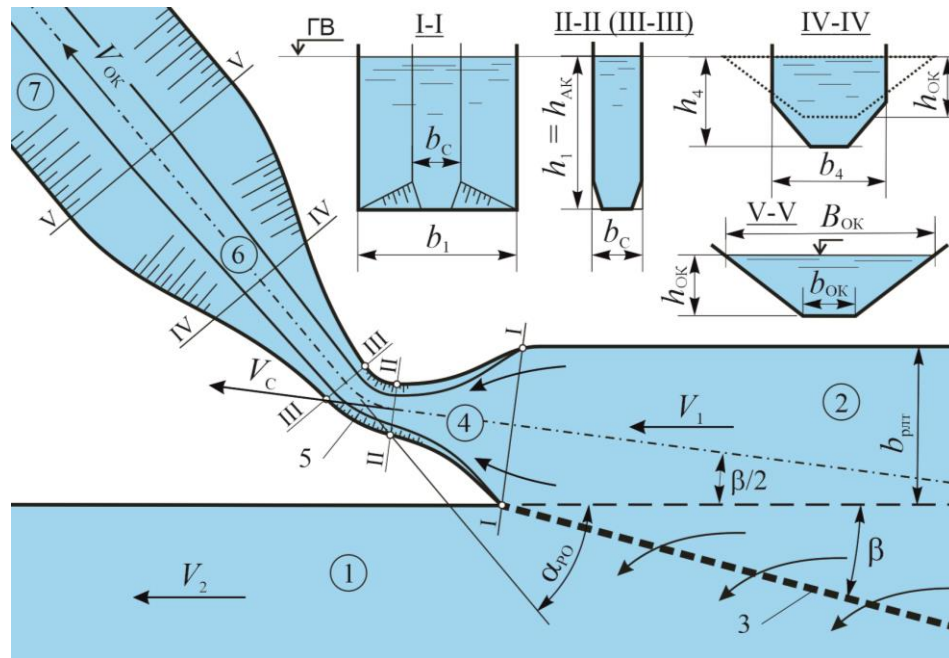


Figure 6. Layout and constructive solution of the inlet portal of open gravity fish outlet
 I-I – V-V – cross-sections of the inlet portal;
 1 – water source; 2 – inlet chamber of fish protection structure; 3 – protective screen;
 4 – entrance area; 5 – receiving area; 6 – transitional area;
 7 – fish-diverting tract

Technically, the portal includes the sequence of the following elements:

- inlet part (entrance area) in the form of a narrowing inlet chamber with a horizontal bottom;
- receiving area (throat) in the form of a narrow prismatic chute;
- transition area in the form of a chute with variable depth and width.

The transformation of the inlet portal cross-section of the fish outlet is represented by cross-sections from I-I to V-V (see Figure 6). The main condition for a continuous flow in the transition (mating) area is the observance of the change linearity concerning its hydraulic diameter at the optimal taper angle θ_{opt} .

4. CONCLUSIONS

The principles of the inlet portal design optimization of open gravity fish outlets are based on a set of sequential basic regularities of the flow planned division, the operation features of nozzles with axial symmetry, the specifics of the conditions for the formation of the flow characteristics on the inlet portal sections, which constructively allows to provide safe hydraulic conditions for the transfer of protected fish into a water source while maintaining its viability.

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