Features of operation and hydraulic calculations

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Abstract. Issues related to the design and hydraulic calculations of the transit part of a closed tubular water supply structure of the siphon type are considered. The operating conditions of a siphon with rectangular pipes in the transition mode are estimated. Due to the formation of a hydraulic jump, the inlet section of the siphon pipes experiences increased hydrodynamic loads, leading to certain defects and destruction. The design of the siphon with two breaks along the length with a portal and a smooth inlet head or without it was modeled. As a result of modeling studies, the absence of a noticeable effect of the inlet head of the culvert on the length of the free-flow inlet section was established. It was revealed that the conditions of formation, the features of the hydraulic operation of the siphon, and the loads it experiences in the transient mode are largely determined by its design solutions. With the flooding of the inlet head, the flow of air into the pipe is hindered, and a transition mode of the second type is formed with a slight fluctuation in the water level in front of the structure upstream. The dependence of the location of the flow separation point with a decrease in the throughput of water on its value was revealed, which made it possible to obtain a graph of the dependence of the relative length of the free-flow section on the square root of the Froude number. A comparison was made with the results of studies by other authors, which showed an increase in the relative length in tubular structures of the siphon type in sections with reverse slopes at the same Froude numbers. Recommendations are given on the methodology for carrying out hydraulic calculation of tubular culverts for various purposes with minimal flow rates, and ways for further multifactorial studies of siphons on the reclamation network are indicated.

1 Introduction

The bases of various water systems are natural or artificial water bodies and their hydraulic structures. At the intersection of channels of water systems with watercourses (streams,

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rivers, gullies, ravines, etc.) or artificial barriers (roads, embankments, canals, communications, etc.) in addition to such water-carrying structures as flumes, aqueducts, storm drains, In slopes and deep recesses, mudflow pipelines, etc., siphon-type closed structures are often arranged: siphons, tunnels, pipes / tubular passages and all kinds of drainage devices during the construction of basic engineering structures.

The siphons are widely used in irrigation, water supply, sewerage systems, hydropower structures, main oil pipelines, road crossings, etc. A feature of the siphons is that their pipelines are located below the bottom of the channels, as a result of which the water flow in them mainly has a pressure flow regime. Culverts should not only ensure the passage of water without violating the safety and continuity of work but also be convenient for the movement of vehicles. Regardless of the material of the culvert, its main characteristics are the shape and dimensions of the hole (width, height, diameter), which determine the throughput of the entire hydraulic structure. Suppose the shape and outline of the pipe opening and its inlet heads are taken for structural reasons. In that case, the dimensions of the pipe openings are justified by hydrological and hydraulic calculations related to the determination of estimated flow rates and runoff volumes.

Regardless of the area of their use, the estimated flow rate of siphon-type structures usually always works under pressure. When calculating the siphon pipes, the Bernoulli equation is used. At the same time, the level of the bottom of the discharge channel is taken as the comparison plane, and all energy losses for the pressure flow in the tubular culvert are taken into account [1-4]. When designing such a structure to ensure its reliable and safe operation on the reclamation network, it is necessary to check for the minimum flow rate [5-7]. This feature of the hydraulic calculation is associated with the possibility of the formation of a hydraulic jump in the pipe, accompanied by hydrodynamic effects on the elements of the transit tract and increasing the likelihood of an emergency state of the elements of the culvert (Fig. 1) [4, 8-10, 16].

a ***b***

Fig. 1. Culverts [4, 16]: *a* is in the Crimea near the city of Simferopol; *b* is in Ingushetia on the Alkhanchurt canal with a pipe defect, 2019

Road pipes, unlike environmental culverts, are usually designed unregulated. The throughput of small pipes is determined by hydraulic calculation of openings, considering the accumulation of a part of the runoff volume in front of the culvert (or excluding accumulation). The initial materials for hydraulic calculation are the estimated flow rate and the calculated water level, the mode of operation of the pipe, the slope of the structure's flume, and the channel's characteristics. The calculation is made according to hydrographs and schedules of design floods. The transitional flow regime, which manifests itself in a periodic change of regimes (non-pressure by pressure and vice versa) and the penetration of air into the structure, is accompanied by an intense pulsation of hydrodynamic pressure, which is dangerous in terms of the reliability (Fig. 2) of structures [1-11]. The intensity of pressure pulsation in the siphon pipe during the transient mode is determined by its type. In the transient mode of the first type, when air bubbles move in the pipe, the pulsation intensity is significantly higher than in the transient mode of the second type, in which a pressure hydraulic jump is formed in the pipe. If the minimum flow rate is skipped, the flow movement will not necessarily be forced along the entire length of the siphon.

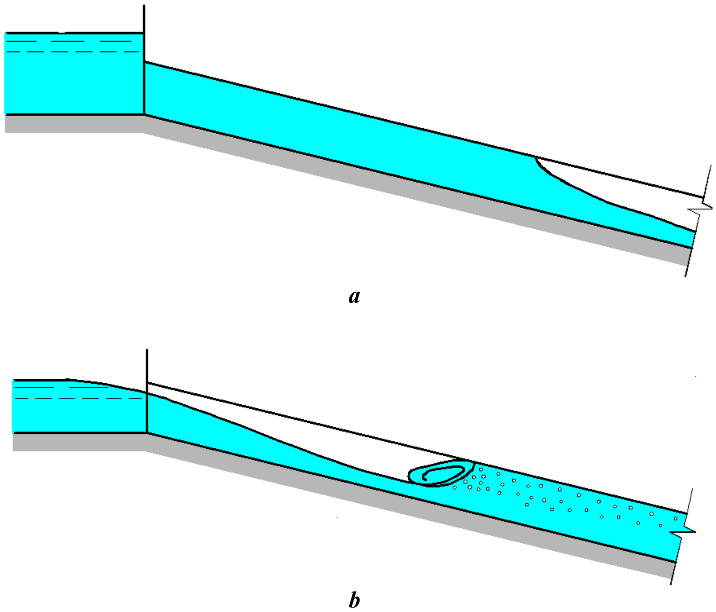

Fig. 2. Possible transition modes of the flow in the initial section of the transit path of a tubular water supply structure [12, 13]: *a* is the first transition mode; *b* is the second transition mode at the entrance portal head.

Thus, in the inlet sloping section, there may be free flow, and if there is a free flow outlet to the downstream, in the part of the outlet section of the siphon with a reverse slope, the flow may also be free flow. At the same time, in the horizontal middle part of the siphon, the pressure movement is preserved.

The verification calculation for determining the hydraulic jump in a pipe of a water-conducting structure is traditionally associated with determining the height position of a piezometric line. To do this, first of all, you need to know where and from which point of the outlet section of the pipe with a reverse slope; you need to start drawing a piezometric line. The answer to this question can be given by the dependence of the length of a non-pressure section with a negative slope at the pipe outlet on some hydraulic parameters.

2 Methods

The position of the point of separation of the flow from the rack at the end section of a horizontal pipe and in pipes with a positive slope was studied by several researchers: Altunin V.I., Rozanov N.P., Babukov Sh.A., Shirchenko V.A., Shvanshtein A.M., Shutko V.K. and others [1, 2, 5-15]. So Sh.A. Babukov established [1] that the location of the separation point, i.e., the relative length of the non-pressure outlet section, depends on the slope. At the same time, Sh.A. Babukov researched a tubular structure with a zero bottom slope and a positive slope equal to 0.0033. Moreover, for relative lengths 22; 30.8; 52, equal to the ratio of the length of the pipe of the culvert to its height with the same slope of the pipeline bottom, the location of the point of flow separation from the ceiling was determined by almost the same dependence.

Altunin V.I. experimental data was obtained, first with smooth rectangular and round, and then with corrugated round pipes [2, 7, 8], which showed the absence of the effect of roughness on the length of the free-flow outlet section of closed culverts, which was confirmed later and by further research by Chernykh O. N. and Burlachenko A.V. for corrugated metal pipes with normal and spiral corrugations [17-21].

When the flow moves in a section of a tubular structure with a reverse slope, which is characteristic of siphon-type structures, detailed studies for pipes with different cross-sectional shapes have not been carried out in the world practice known to the authors. Therefore, studies were organized in the MADI hydraulic laboratory to determine the length of a non-pressure section with a negative slope on the siphon model (Fig. 3). The laboratory setup was made of plexiglass, the model of the siphon pipe had a square cross-section with a height of a = 10 cm, the slope of the inlet section was 0.32. The total length of the model was about 4 m. Before entering the pipe; a damper was installed, consisting of horizontal tubes with a diameter of 2 cm. A tubular culvert with a smooth-shaped inlet head and without an inlet head was modeled; a little later, additional studies were carried out with a "hood" type head, occasionally used on reclamation systems [5]. Preliminary experiments indicated that there was no practical effect of the inlet head of the siphon on the length of the non-pressure section.

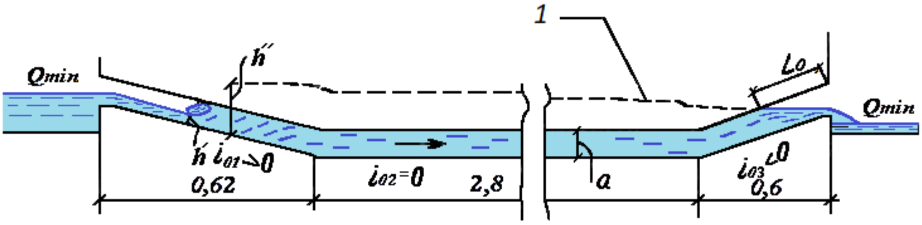

Fig. 3. Schematic diagram for the estimated hydraulic calculation of the siphon with a sharp decrease in water throughput: 1 is piezometric line.

3 Results and Discussion

As a result of the experimental studies, the dependence of the location of the flow separation point on the water flow was revealed, which made it possible to obtain a graph of the dependence of the relative length of the free-flow section Lo on the square root of the Froude number $\sqrt{Fr}$ (Fig. 4). The Froude number Fr was calculated for the pressure section of the flow according to the dependence

$$Fr = \frac{V^2}{ga} = \frac{Q^2}{ga^5} \quad (1)$$

where V is the average flow velocity, m/s; $g = 9.81\, m^2/s$; a is the height of a rectangular pipe or the diameter of a round one, m.

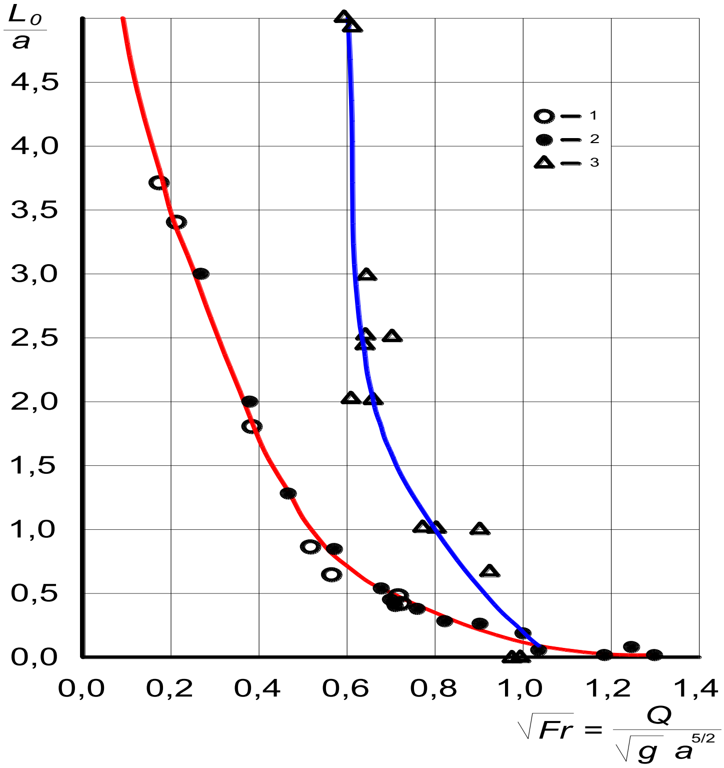

Fig. 4. Dependence of the relative length of the non-pressure section at the outlet of the siphon (*Lo/a*) on the parameter $\sqrt{Fr} = (Q/\sqrt{g}\ a^{5/2})$: 1 is at $i = -0.32$ for a siphon with a tip; 2 is at $i = -0.32$ for a siphon without a head; 3 is at $i = 0$ according to Sh.A. Babukova [1].

The resulting graphical dependence in figure 4 is valid for smooth pipes with a negative slope of 0.32. For comparison, the graph shows the experimental data of Sh.A.Babukov, relating to a tubular structure with a zero slope and smooth pipes. Comparison of the obtained data with the data of Sh.A.Babukov shows an increase in the relative length in tubular HTS with reverse slopes at the same Froude numbers. Apparently, in the outlet sections of pipes with a reverse slope, the effect of gravity at low Froude numbers, i.e., with relatively small inertial flow forces, it affects to a greater extent than in GTS pipes with a horizontal inlet section.

An exponential (fig. 5) and polynomial approximation of the experimental data was performed, which made it possible to obtain the corresponding calculated dependences (2) and (3), using which one can find, knowing the Froude number, the optimal length of the free section.

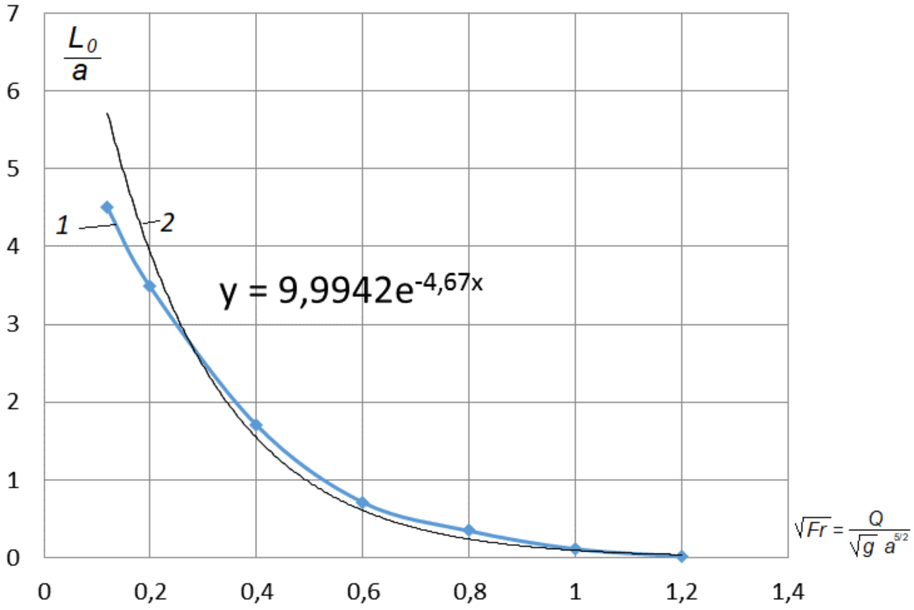

Fig. 5. Exponential approximation of the graphical dependence $(L_o/a) = f\,(\sqrt{Fr})$: 1 is experimental line, 2 is exponential line.

Exponential dependence:

$$L_0 = 9.99ae^{-4.67\sqrt{Fr}} \qquad (2)$$

Polynomial dependency:

$$L_o / a = -5.54\, Fr^{3/2} + 16.77\, Fr - 17.42\, Fr^{1/2} + 6.35 \qquad (3)$$

For use, a simpler formula (2) is recommended, confirmed by experiments for pipes of the rectangular and round cross-section with an error of no more than 6%

Thus, depending on the parameter $(Q/\sqrt{g}\ a^{5/2})$, it is possible to determine, using the graph in Figure 4, the relative length of flow separation from the rack (ceiling) L_o/a, and then, using well-known methods, calculate the position of the piezometric line [15, 19, 21]. The hydraulic jump will be where the piezometric line will be crossed by the second conjugate depth line calculated for the free flow depths in the inlet section, essentially the first conjugate depths.

The appearance of a hydraulic jump at the inlet section of the siphon should be avoided [5, 8, 21]. The pressure pulsations that occur in a hydraulic jump when the jump moves in a pipe (Fig. 5) adversely affect the operation of any water-conducting tubular structure. At the same time, the seams can be disturbed, and other local defects may occur in the transit part (Fig. 1b) [4, 12, 13, 16, 18].

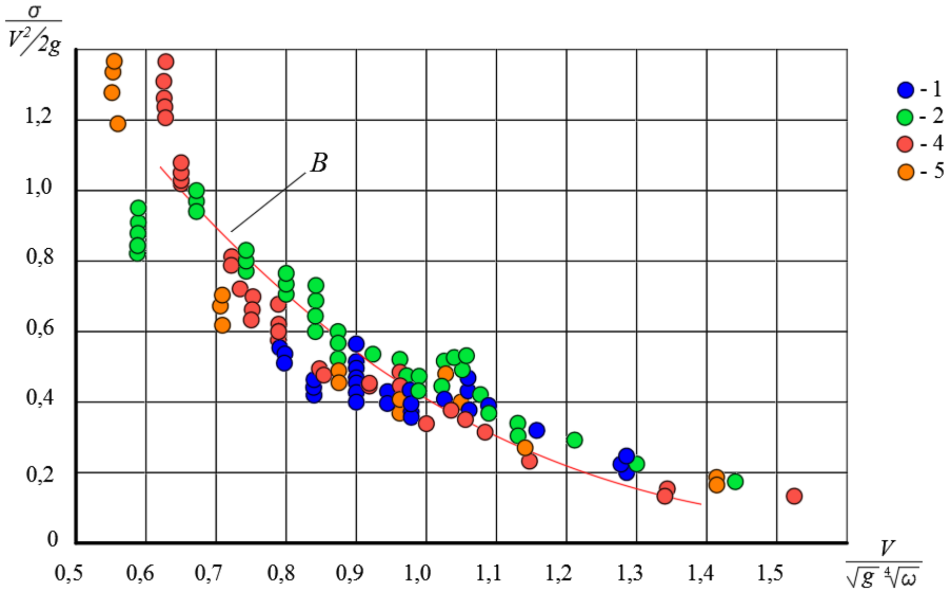

Fig. 6. Plot of dependence $\frac{\sigma}{V^2/2g} = f\left(V/\sqrt{g}\,\sqrt[4]{\omega}\right)$ for a siphon with a portal inlet head: 1 – 5 are experimental points in the corresponding different measured sections of the siphon pipe; *B* is averaging line.

The pressure pulsation intensity is unevenly distributed along the length of the inlet section of the pipe transit path, which corresponds to an unflooded jet inlet and the presence of a second-type transient mode on it. Since the main source of pressure pulsation, in this case, is the hydraulic jump, the pulsation sharply increases in the sections closer to it, the standard. Accordingly, in the end sections, the pulsation intensity is minimal, and with an increase in flow, the pulsation intensity in all sections noticeably weakens. At the same time, as the results of multifactorial studies show, one of the determining factors in the hydrodynamic process is the design of the inlet head, especially in the first type of transient mode [2, 5, 10, 17]. Moreover, the minimum pulsating load is just observed at the portal head (Fig. 5 and 6), and the head with smooth continuous forms can cause the greatest pulsation load on the elements of the water-carrying tract of a particularly closed culvert.

4 Conclusions

If a hydraulic jump is formed in a culvert pipe with given geometric dimensions, then its cross-section can be reduced. In this case, the Froude number will increase, the flow separation length will decrease, the piezometric line will rise, and the inlet section will be able to get stuck; that is, the hydraulic jump will disappear. However, if, in this case, there is a possibility of a significant reduction in the throughput of a siphon-type structure, which is unacceptable for a reliably operating reclamation system, then it is necessary to calculate the inlet section already taking into account the increase in the pulsating load from the hydraulic jump. To optimize the design solutions of siphons operating in a wide range of changes in the determining parameters of the hydraulic regime, it is necessary to conduct further multifactorial studies with tubular culverts of various typologies.

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