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HYDRODYNAMIC INVESTIGATIONS OF INVERTED SYPHON'S FRAGMENT

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ABSTRACT

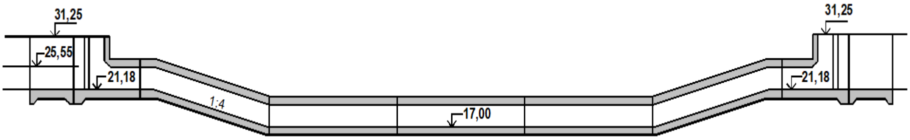
In this article are presented the results of studying the operating conditions in the transient mode of an inverted syphon with rectangular pipes, which at the same time experience increased hydrodynamic loads, often leading to one or another destruction. Also are presented the results of the study of pressure fluctuations in various sections of the bottom along the length of the transit part of a tubular structure of a inverted syphon type with a rectangular cross section. Was modeled the design of the inverted syphon with two breaks along the length and three types of inlet portals: smooth, "hood" type and portal wall. It has been established that the conditions of formation and features of the hydraulic operation of the inverted syphon in the transient mode are mainly determined by its design features. With the flooding of the inlet portal, the flow of air into the pipe is hindered and a transition mode of the second type is formed. At a certain flow rate, depending on the design of the input "self-charging" portal (of the "hood" type or smooth), the second type of transient mode is replaced by the first. Level fluctuations in the headrace in the both cases are insignificant. Also, is given the data on the distribution of the pulsating pressure component, its intensity and spectral density in various sections along the length of the pipe. The maximum intensity of pressure pulsation (the ratio of the pressure pulsation standard to the velocity head in the pressure section of the pipe) is observed with a hood-type portal – 1.3 (with a flow rate parameter of 0.95). With a smooth portal it is slightly lower (about 0.95 at a flow rate of 1.19), but the highest standard of pressure pulsation occurred with a soft portal and corresponded to high flow. The maximum was in the measuring section, located at the beginning of the horizontal section of the pipe. Recommendations are given on establishing the boundaries of the existence of a transient mode and on the intensity of pressure pulsation in various sections along the length of the pipe with an analysis of the spectral characteristics and a discussion of measures that ensure a decrease in pulsation during transient modes. In the initial phase of the transition mode, the spectrum is mainly narrow-band with a frequency of about 0.28 Hz, and with an increase in the frequency of air bubbles, it expands and the leading frequency of pulsation oscillations increases. At maximum loads, the leading frequency of the pressure pulsation is located in the infra-frequency zone. With the onset of the pressure mode, the leading frequency approached 3 Hz. A comparison with the results of studies by other authors is given. It has been established that the existing recommendations on setting the maximum intensity of pressure pulsation in tubular structures during transient conditions (no more than 0.2) are valid only for specific types of the studied structures and their operating conditions.

Keywords: flow mode, pipe work, intake portal, transient mode, inverted syphon, pressure pulsation.

INTRODUCTION

Unregulated and adjustable tubular structures are often used in the practice of constructing spillways of waterworks, road pipes under embankments, inverted syphons (Fig. 1), culverts on reclamation canals: downstream currents, water meter regulators with a crossing (with and without a drop), mine drops on irrigation network, wash pipes, etc.

The flow regime within the transit part of a tubular culvert hydraulic structure can be free-flow, transitional, partially-pressure and pressure. The transitional flow regime, which manifests itself in a periodic change of regimes (non-pressure pressure and vice versa) and the penetration of air into the structure, is accompanied by an intense pulsation of the hydrodynamic pressure, which is dangerous in terms of reliability (Fig. 2) of the hydraulic structure (Chernykh, 2021; Handbook, 2007; Kosichenko et al., 2014; Bandurin, 2012; Shvanshtein and Obukhov, 1984; Shvanshtein, 1986; Altunin, 1988; Altunin and Chernykh, 1990; Rice, 1966; Shvanshtein, 1997; Shutko, 1981). The intensity of pressure pulsation in a tubular hydraulic structure during the transition 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. However, the data of experimental hydrodynamic studies of models of tubular structures cited in the literature show that in a number of cases the pressure pulsation under the same type of transient modes differs significantly. This indicates the influence of not only the type of transient mode on the pulsation, but also other factors, which indicates the need for further research.

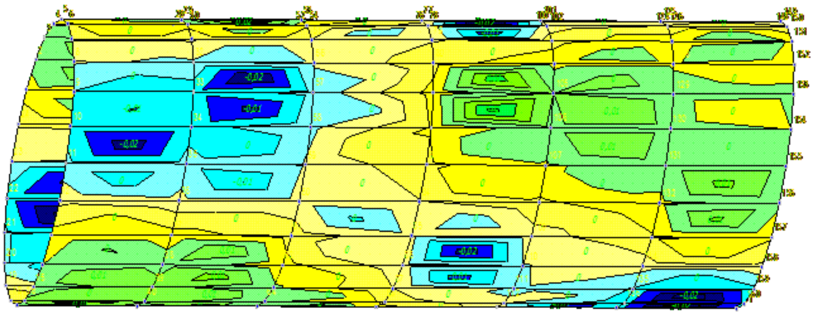


(a)

(b)

Figure 1: Scheme (a) and view of the outlet head (b) of the inverted syphon of the Donskoy main canal across the river. Sal, Russia (Kosichenko et al., 2014)

(a)

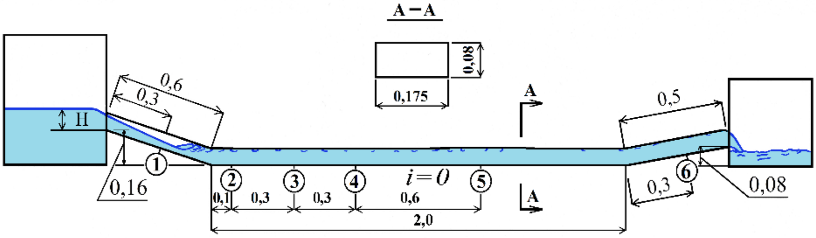


(b)

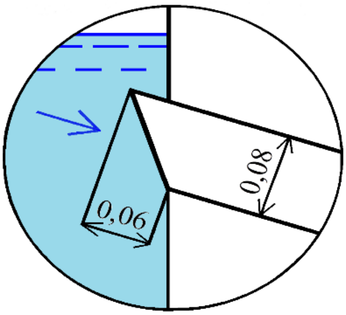
Figure 2: An example of the formation of a defect in the syphon pipes [4]: a - outside the long-term operated Tashlinsky syphon on the Pravo-Egorlyk Canal; b - diagram of excess equivalent stresses according to von Mises in the places of defect formation

METHODS

The overview of qualitative and quantitative changes in the hydrodynamic pressure fluctuations for various designs of the inlet portal on the water-carrying tract when changing modes was analyzed using pressure fluctuation sensors and secondary recording equipment. A model of a tubular hydraulic structure of a syphon type with a rectangular pipe shown in Fig. 3 was already studied (Shvanshtein and Obukhov, 1984; Altunin and Chernykh, 1990). The water supply system of the models existed in closed circulation. Three designs of the inlet portal were considered: the currently rarely used “hood” portal, the most demanded culvert outlet, as well as a smooth portal with a curvilinear outline of the top and bottom faces and flat side walls. In comparison, the culvert outlet is the simplest in construction, but with such a design scheme it is quite difficult to ensure the smooth flow of the watercourse. The culvert of the "hood" type belongs to the class of self-loading, which determined the expediency of its study. The culvert outlet end was portal.



(a)



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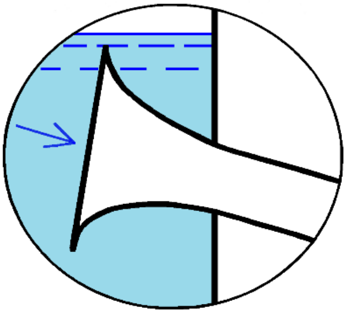

(c)

Figure 3: Principal scheme of model installation: a – with a portal culvert oulet; b - outlet of the "hood" type; c - smooth outlet with vertical rectilinear side walls; 1 to 6 - measuring sections

When conducting hydrodynamic studies inductive-type sensors were used, and the standard of pressure fluctuations σ, in accordance with a common technique, was determined assuming the distribution of fluctuations according to the normal law (Altunin, 1988; Altunin and Chernykh, 1990; Chernykh and Khanov, 2017; Chernykh and Komelkov, 1983).

RESULTS AND DISCUSSION

In conjugated culverts usually takes place the transitional mode of the first type, when part of the pipe from the side of the culvert inlet begins to work under pressure at low pressures, it is possible with a non-flooded outlet section (Fig. 4). The main source of pressure pulsation during the transient mode of the first type in tubular hydraulic structures is a pressure hydraulic jump, which exists under conditions of vacuum pressure at the inlet. Air entering the pipe from the side of the culvert inlet changes the vacuum pressure at the inlet, which also increases the pulsation in the pipe.

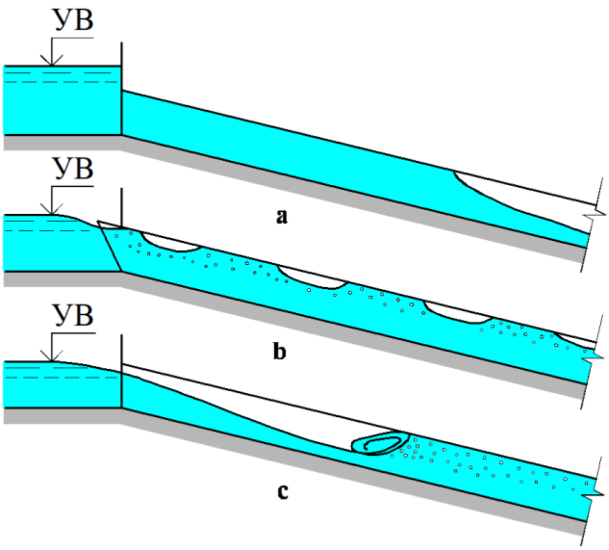

Figure 4: Transitional modes of flow in the initial section of the syphon culvert: a - the first transitional mode: b - the second transitional mode with a self-loading portal of the "hood" type; c - the second transitional mode with a non-self-charging portal culvert inlet

Simultaneous observations of the formation of single air bubbles in the initial phase of the first type of transient mode and the pressure pulsation in the pipe at the same time on the monitor screen showed that a burst of pulsation was observed at the initial moment of the formation of an air bubble. That is, the main source of pressure pulsation was the inflow of air into the region of vacuum pressure at the inlet inclined section (the size of the bubble corresponded to the length of this section). After the end of the process of formation of the air bubble, the flow of air into the pipe stopped, the pulsation decreased, and the bubble began to move. Getting on the horizontal section of the pipe, the air bubble flattened at its arch and moved to the exit. There was no noticeable change in the pressure pulsation in the pipe during the movement of the air bubble. Thus, the obtained experimental data do not quite coincide with the statement of Shvanshtein that “the main cause of pressure pulsation when moving with the flow of air cavities is water hammer caused by a change in the capacity of the conduit" (Shvanshtein and Obukhov, 1984; Shvanshtein, 1986; Shvanshtein, 1997). On all the studied models of the inverted syphon pipe, with an increase in flow rate in the transient mode of the first type, both the size of air bubbles and the time of their formation, as well as the value of the vacuum pressure at the inlet, decreased. This increased the number of air bubbles in the pipe at the observed time.

The flooding of the "hood" culvert inlet occurs on the model at parameter

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}} = 0.71$$

where V is the average flow velocity, g = 9.81 m^2/s, ω - is the cross-sectional area of a rectangular pipe), but charging occurs only at

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}} = 0.81$$

after which forms the transition mode of the first type. In the range of values 0.71 to 0.81 there is a transient mode of the second type, which was replaced by a transient mode of the first type (Fig. 5). With a non-flooded culvert inlet, when free-flow movement is observed at the inlet inclined section, as well as in the second type of transient mode with a pressure hydraulic jump in the pipe, the pulsation intensity in all measured sections behind the hydraulic jump is approximately the same (sections 2 to 6). As consumption increases, it decreases. After the onset of the first type of transient regime, the pulsation is redistributed along the length of the pipe. The maximum is observed in the second alignment, and the minimum is in the fifth and sixth. With a further increase in flow in all sections, except for the first and second, the intensity of pressure pulsation decreases. In the marked sections, with an increase of

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}}$$

from 0.81 to 0.94, the intensity of the pulsation increases, and at

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}} = 0.94$$

it decreases. Moreover, if in the initial section of this range the intensity of pulsation in these sections is approximately the same, then at

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}} > 0.94$$

in the second section it is significantly higher (by about 50%). Pulsation equalization in the first and second sections is observed at

$$\frac{V}{\sqrt{g\sqrt[4]{\omega}}} > 1.0$$

In the initial phase of the pressure mode at

$$\frac{V}{\sqrt{g}\,\sqrt[4]{\omega}} = 1.1$$

when the flooding of the inlet tip is small and a small amount of air periodically breaks into the pipe, there is an uneven distribution of pressure pulsation along the length of the pipe, but with an increase in flow rate, the pulsation levels off.

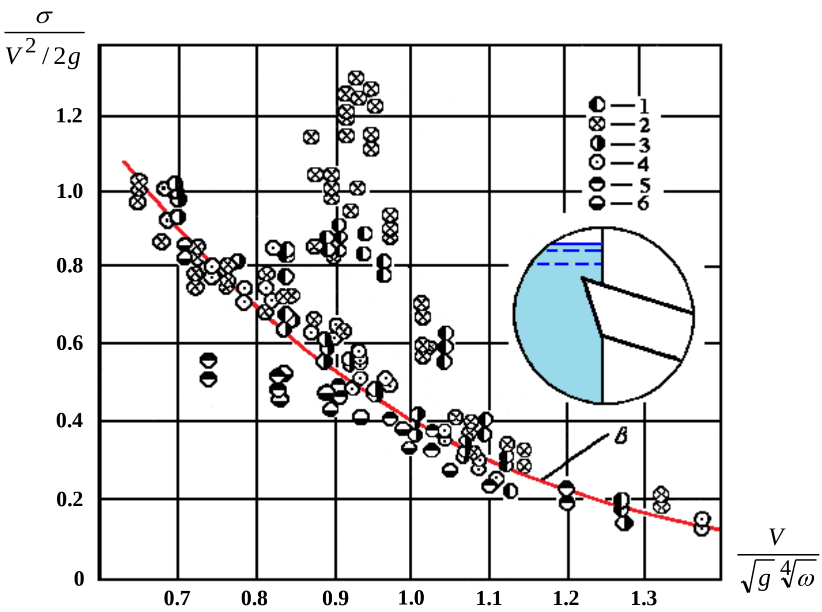

Figure 5: Intensity of pressure pulsation $\sigma/(V^2/2g) = f\left(\frac{V}{\sqrt{g}\,\sqrt[4]{\omega}}\right)$ for a model with an inlet culvert of the "hood" type in the corresponding measuring sections (1 to 6): *B* – averaging line for determining σ

The data obtained from experimental studies can be approximated for a tubular structure of a syphon mode with a "hood" inlet culvert, which is currently relatively rarely used in the reclamation systems of Russia for a number of reasons and can be described by the dependence:

$$\frac{\sigma}{V^2/2g} = 6.72\left(\frac{V}{\sqrt{g}\,\sqrt[4]{\omega}}\right)^{-2.87} \quad (1)$$

With the flooding of the portal inlet culvert in the pipe in the range

$$\frac{V}{\sqrt{g}\,\sqrt[4]{\omega}} = 0.7 - 1.12$$

a transition mode of the second type is formed, which is then replaced by a pressure mode. With an increase in a flow rate, the hydraulic jump located within the inlet inclined section moves in the direction of the inlet tip. At

$$\frac{V}{\sqrt{g}\sqrt[4]{\omega}} = 1.05$$

the hydraulic jump, located within the inlet culvert, actually disappears. There is an air bubble of variable mass that breaks off periodically. But here it is formed again due to the air breaking through the pipe. At flow rates corresponding to an non submerged inlet culvert and a transient regime of the second type, there is some uneven distribution of the intensity of pressure pulsation along the length of the pipe (Fig. 6). This is explained by the fact that the main source of pulsation is the hydraulic jump located at the beginning of the central horizontal section or at the inlet inclined section. In the sections located closer to the hydraulic jump, the pulsation intensity is higher. Therefore, the smallest pulsation is observed in the end sections, and the largest - in the initial ones. In the pressure regime, the pulsation in all sections is determined by the turbulence of the flow, which varies insignificantly along the length. As the flow rate increases, the pulsation intensity in all sections decreases.

Curve B is plotted on the graph (Fig. 6), averaging the experimental points in 3...6 sections with a hood-type culvert inlet (Fig. 6). This curve fairly satisfactorily averaged the experimental points at the portal tip. Therefore, the hydraulic effect of the flow on the pipe walls with a portal culvert inlet and in the area behind the 3rd section with a "hood" culvert is approximately the same. With a portal culvert inlet, the inlet section experiences significantly less pulsating loads than with a hood-type culvert inlet, therefore, a tubular structure with this culvert inlet is in more favorable conditions.

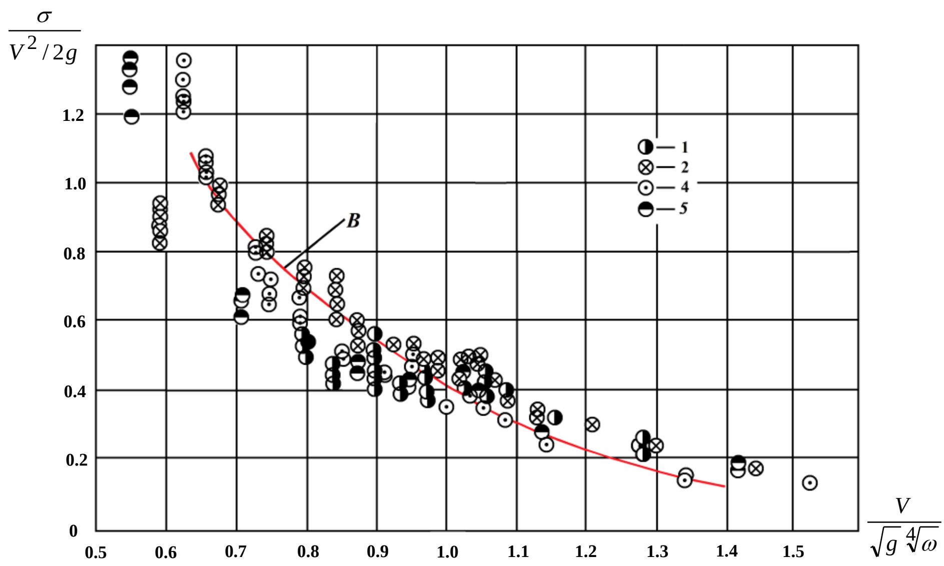

Figure 6: Intensity of pressure pulsation σ/(V²/2g) = *f* ($\frac{V}{\sqrt{g}\sqrt[4]{\omega}}$) for the model with a portal inlet culvert: 1 to 5 – experimental points in the corresponding measuring sections along the axis of the inverted syphon pipe; B - averaging line from Fig. 5

With a smooth culvert inlet, as it is flooded and has parameters 1.09-1.19, a second type of transition mode is formed in the syphon culvert. At

$$\frac{V}{\sqrt{g}\sqrt[4]{\omega}} > 1.2$$

it is replaced by a transitional regime of the first type. At the same time, pressure pulsation is observed in the second section compared to increased risks of development, but not as significantly as with a "hood"-type inlet culvert or with a smooth inlet head with all curvilinear dimensions (Fig. 7). With the parameter

$$\frac{V}{\sqrt{g}\sqrt[4]{\omega}} = 1.42$$

the mode becomes pressurized.

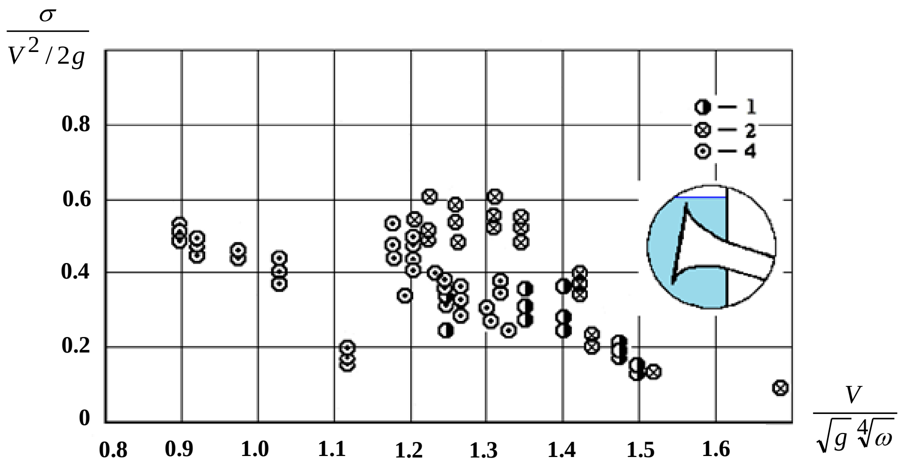

Figure 7. Pressure fluctuation intensity σ/(V²/2g) = *f* ($\frac{V}{\sqrt{g}\sqrt[4]{\omega}}$) for the model with a smooth inlet tip: 1, 2, 4 – experimental points in characteristic measuring sections along the syphon culvert axis

Thus, the design of the inlet culvert has a strong influence on the pressure pulsation during the first type of transient. The maximum pulsation intensity with a hood-type culvert inlet reaches $\sigma/(V^2/2g) = 1.3$ at

$$\frac{V}{\sqrt{g}\sqrt[4]{\omega}} = 0.95$$

and with a smooth culvert inlet with side faces of a curvilinear shape $\sigma/(V^2/2g) = 0.96$ ($\frac{V}{\sqrt{g}\sqrt[4]{\omega}} = 1.19$), and with a smooth culvert inlet with flat side faces $\sigma/(V^2/2g) = 0.55$ at $\frac{V}{\sqrt{g}\sqrt[4]{\omega}} = 1.22 \ldots 1.31$, that is, the smallest. The fact is interesting and important, since only a change in the shape of the side faces of the smooth head from curved to straight can significantly reduce the pulsating load. This is explained by the fact that the side walls of a rectilinear shape, in contrast to the curvilinear ones, provide a smooth compression of the flow. Therefore, the costs at which the floating head with vertical side walls are flooded and charged are slightly increased. And this, in turn, affects the conditions for the formation and size of air bubbles, which are the main sources of pulsation (Chernykh et al., 2020; Altunin, 2016). The maximum intensity of pressure pulsation is still observed more with a smooth head with all curvilinear faces. This is due to the fact that the maximum pulsating loads of such heads are observed at different flow rates. The spectral characteristics of the pressure pulsation of these tips under the same modes are similar.

At the maximum pulsation intensity (in the second section), the spectra are narrow-band with the maximum located in the frequency zone below 1 Hz, which corresponds to the features of the transition mode (Fig. 8). That is, in the initial phase of the transition mode of the first type, the dispersion of pressure fluctuations is determined by the conditions for the formation of single air bubbles. With an increase in the frequency of movement of air bubbles in the experiment, the spectrum expanded, and the leading frequency of pulsation oscillations increased. Thus, in the initial phase of the first type of transient mode, the leading frequency was 0.18 – 0.28 Hz, and at the end it exceeded 1 Hz. Behind the second alignment, the zone of energy-carrying frequencies also expanded and the value of the leading frequency increased. In the transient mode of the second type, the leading pulsation frequency was about 0,6 Hz, but the main contribution to the dispersion of pressure fluctuations here is made by components in the range 1.5 to 5 Hz, the spectral values of which are close to the maximum. With the onset of the pressure mode, the pulsation spectrum expanded even more, and the leading frequency approached 3 Hz.

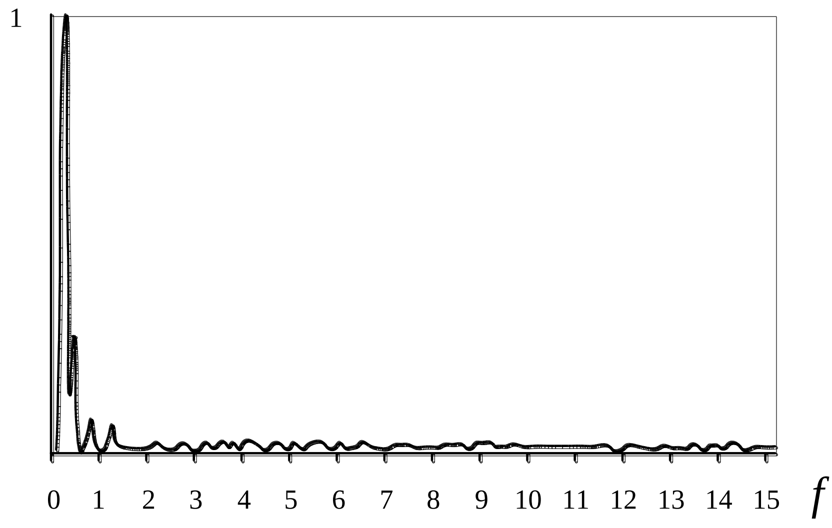

Figure 8: The normalized function of the spectral density of pressure fluctuations in the second section at $\frac{V}{\sqrt{g}\sqrt[4]{\omega}}$ **= 1.19**

The results obtained are in qualitative agreement with the data of other authors. So, Shutko (1981) notes that “a surge of pressure pulsation is observed when passing the end of the plug” (the place of a pressure jump in vacuum conditions), which, on the studied model of the syphon, was at the end of the inlet inclined section during the formation of the air bubble. Leading energy-carrying frequencies according to A.M. Shvanshtein [6] are in the frequency range below 1 Hz, which also corresponds to our data. However, according to Shutko (1981) and Shvanshtein (1984, 1986, 1997) no more than 0.25 and 0.3, respectively. This difference can be explained by the design features of the studied structures. As noted, the largest pressure pulsation was observed at the end of the inlet inclined section of the studied syphon model and was caused by a "pressure jump in the vacuum zone". The values of the vacuum pressure in the initial section of the models under consideration, proportional to the slope, were different, for example, in the experiments of Shvanshtein, the slope of the spillway model did not exceed 0.02 while Shutko (1981) it is of 0.0375, and the slope of the initial section of the investigated syphon model was 0.267.

Comparison with the data of studies of culverts made of metal, including those with different types of corrugations, shows that the recommendations received cannot be transferred to other types of structures in which the pulsation intensity can differ significantly with both increase and decrease. Therefore, it is necessary to conduct comparative studies to assess the dynamic loads from the flow on innovative culvert designs from corrugated structures, which have been widely introduced especially intensively in road construction in recent years (Suetina , 2018; Suetina et al., 2020).

CONCLUSION

The largest pressure fluctuation in the syphon culvert was observed in experiments with the first type of transient mode in its initial phase, i.e. when moving through the culvert of single air bubbles. The maximum intensity of pressure pulsation (the ratio of the pressure pulsation standard to the velocity culvert inlet in the pressure section of the pipe) was 1.3 with a hood-type culvert inlet (with a flow parameter of 0.95). With a smooth culvert inlet, it is slightly lower (about 0.95 at a flow rate of 1.19), but the highest standard of pressure pulsation was still observed in the siphon culvert with a soft head, because he was spending a lot of money. The maximum pressure pulsation corresponds to the alignment located at the very beginning of the horizontal section of the culvert. The minimum pulsating load is observed at the portal culvert inlet. The spectrum of pressure pulsation in the maximum load section (No. 2) is broadband with a leading frequency of about 3 Hz. The main energy-carrying frequencies are in the range from 1 to 5 Hz.

An analysis of the change in the spectral density of pressure fluctuations confirmed the connection between hydrodynamic processes and the change in the type of transient mode in the culvert of the hydraulic structures of the syphon type. The performed studies show that the pressure pulsation in a tubular structure during the transient mode depends not only on the type of mode, but also on the design features of the inlet head. The tip with smooth non-separated surface forms provides not only the largest area of flow rates with transient conditions in a specific siphon-type hydraulic structure, but also the largest pulsation loads. Replacing curvilinear faces at the smooth head with straight ones leads to a significant reduction in the pulsation load on the elements of the inlet section of the transit part of the pipes and, in general, leads to an increase in the reliability of the operation of the entire environmental hydraulic structure.

REFERENCES

ALTUNIN V.I. (1988). Pulsation of pressure in a tubular structure during the transitional regime // Proceedings of MADI, Vol. Hydraulics of vehicles and road structures. M.: MADI, S., pp. 67-71.

ALTUNIN V.I., CHERNYH O.N., BURLACHENKO A.V. (2016). Hydraulic Resistance of Corrugated Metal Culvert Pipes with Elevated Abrasive Resistance, Power Technology and engineering, November, Vol. 50, Issue 4, pp. 385-390.

ALTUNIN V.I., CHERNYKH O.N. (1990). Influence of the design of the inlet head on the pressure pulsation in a tubular structure during the transitional regime, Proceedings of MADI, Vol. Calculations of elements of hydraulic systems of machines and mechanisms, M.: MADI, S., pp.73-79.

ALTUNIN V.I., CHERNYKH O.N. (2016). Hydraulic Resistance of a Helially Corrugated Metal Pipe Culvert, Power Technology and engineering, Vol. 50, Issue 10, pp. 125-129.

BANDURIN M.A. (2012). Finite element modeling of the stress-strain state of the Tashlinsky syphon on the Pravo-Egorlyksky canal, Monitoring, Science and security, No 2.S., pp.102-106.

CHERNYKH O.N., ALTUNIN V.I., BURLACHENKO A.V. (2015). Experimental studies of a metal corrugated culvert under partial pressure mode, Privolzhsky Scientific Journal, No 1 - S., pp. 28-36.

CHERNYKH O.N., BURLACHENKO A.V. (2021).Operation and design of syphons at water bodies [Electronic resource], Russian State Agrarian University – Moscow, Timiryazev Agricultural Academy (Moscow). - Electron. text data-Moscow, 151p. phttp://elib.timacad.ru/dl/local/06122021.pdf/info.

CHERNYKH O.N., KHANOV N.V. (2017). Methodology for improving the educational process in the laboratory complex of the department of hydraulic structures // Bulletin of the educational and methodological association for education in the field of environmental management and water use, No 10, S., pp. 44-52.

CHERNYKH O.N., KHANOV N.V., BURLACHENKO A.V. (2019). Evaluation of the influence of inlet devices on the hydraulic conditions of operation of various modifications of corrugated metal tubular road crossings, Doklady TSHA, Vol. 291, part III, 59 pp., pp. 74-78.

CHERNYKH O.N., KOMELKOV L.V. (1983). Hydrodynamic loads and stability of river beg protection downstream of hydraulic structures, Abstracts XX Congress IAHR, Vol. VII, - M.

CHERNYKH O.N., SUETINA T.A., BURLACHENKO A.V. (2020). Scientific bases for improving the methods of hydraulic calculation of road corrugated metal pipes, M.: MADI, 234 p.

HANDBOOK of Steel drainage and highway construction products (2007). Published C.S.P.I., Second Canadian Edition, Cambridge, Ontario, Canada, Second Printing, November.

KOSICHENKO YU. KOSICHENKO M., BAEV G.L., YU. A. (2014). Garbuz - Novocherkassk: FGBNU "RosNIIPM", 49 p.

RICE C.E. (1966). Friction factors for helical corrugated pipe. U.S. Department of Agriculture. ARS 41-119, Agriculture Research Service, Washington, D.C., February.

SHUTKO V.K. (1981). Studies of transient regimes in water conduits of closed section, Abstract diss. for the competition scientist degree cand. tech. Sciences, L., 16 p.

SHVANSHTEIN A.M. (1986). Construction tunnels. hydraulic operating conditions, M., Energoatomizdat, 123 p.

SHVANSHTEIN A.M. (1997). Hydraulic operating conditions of tubular and tunnel spillways, Izv. VNIIG, No 230, S., pp. 287-313.

SHVANSHTEIN A.M., OBUKHOV A.G. (1984). Limits of the existence of partially pressure flow regimes in unregulated tunnel spillways, Izv. VNIIG, No. 170, pp. 54-60.

SUETINA T.A., CHERNYKH O.N., BURLACHENKO A.V. (2018). Hydraulic calculation features of helically corrugated steel culverts, IOP Conference Series: Materials Science and Engineering, VII International Symposium Actual Problems of Computational Simulation in Civil Engineering, 1–8 July, Novosibirsk, Russian Federation, Vol. 456, Section 4, December, 5 p.

SUETINA T.A., CHERNYKH O.N., BURLACHENKO A.V., KOROTEEV D.D. (2020). Hydraulic parameters of culverts from pipes with normal and spiral form of corrugation, International Conference on Engineering Systems, Journal of Physics, Conference Series 1687, 012037.