Estimation of hydrodynamic loads acting on downstream fastening plates of low-pressure tubular structures

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Abstract. In the article are presented the results of the state analysis of low-pointed tubular culverts widely used in land reclamation and fisheries construction, the lower pool of which is made in the form of an expanding socket with a central angle of 30^0 to 60^0 and checker-type energy absorbers. Field surveys have shown that only in the Moscow region such structures, built mainly in the 60-70s of the last century, makeup 76% of the total number of structures on water systems. The condition is from 70% to 85% of them, depending on the region unsatisfactory: the dampers are deformed and even shifted, the lining of the water break and the apron is destroyed, excessive erosion is observed in the discharge channel. The results of experimental studies of the averaged and pulsating pressure on the downstream attachment elements (the bottom of the water break in the flooded hydraulic jump zone and the initial sections of the apron), performed at Reynolds numbers (20...75) 10^3 on a model installation of a 3-point sluice-regulator, showed that a change in the angle of the bell and the energy parameter within 1.5...4.5 does not affect the nature of the longitudinal and transverse distribution diagrams of the average pressure in the bell and behind it. As a result, universal schemes of static loading by a vertical averaged load from a surface flow have been developed. In the discharge channel and on the slopes, the pressure fluctuation occurs mainly due to surface disturbance; therefore, a low-frequency component is traced on the autocorrelation functions, which also determines the spectrum's shape. It is proved that when constructing a quasi-static loading of plates by an instantaneous pulsating load for an expanding water break with triangular spreaders and checker-type dampers, it is possible to correctly use the longitudinal and transverse correlations corresponding to spatial turbulence and on the apron-homogeneous. The maximum amplitude of the pulsating load on plates of any size should be calculated with a transition coefficient equal to approximately 3.85 for apron plates and no more than 4.5 for water breakage. The results obtained make it possible to perform the entire complex of calculations to assess the stability of various elements of the downstream structures of the considered typology.

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1 Introduction

The downstream of tubular culverts and crossings on highways is often made in the form of an expanding bell (the value of the central bell angle Θ is from 30^0 to 60^0), at the bottom of which checker-type energy absorbers are installed. Analysis of design solutions for one-, two- and three-point tubular structures, built and surveyed low-pressure hydroelectric facilities in the Moscow Region (MO), carried out by employees of the Department of Hydraulic Structures of the Moscow Irrigation Institute, and then the Institute of Land Reclamation, Water Management, and Construction named after A.N. Kostyakov of the Russian State Agrarian University - Moscow Agricultural Academy named after K.A. Timiryazev from 1973-2022 showed that these structures, which have been in operation for more than 60 years, were in an unsatisfactory condition during field surveys (from 70% to 85% in different areas of the Moscow Region), a small proportion of them are still functioning, but an emergency can happen on them at any moment [1-4]. Usually, methods developed for massive fastenings of high-pressure tubular structures are used to calculate the elements of fastenings for the downstream of low-pressure structures. In some cases, this leads to a significant overestimation of the stability margin of the attachment plates, especially prefabricated ones, or the deformation of not only the apron and the outlet section but also to the loss of stability of the energy absorbers in the water hole (Fig. 1).

Fig. 1. Results of tubular culverts surveys held in Moscow Region, built according to standard designs of different years [3,5] (photo by the authors): a is deformation of fastening of downstream of single-point tubular crossing from corrugated pipe and gabion structures on Moscow-Kolomna highway, 2021; b is water well with dampers-spreaders behind two-point spillway of pond on river Chernichka in Podolsk region in 2009; c is fragments of building structures in pipe and at beginning of water well of dam on river Solovka, Podolsky district, 2019; d is displacement of absorber of second row of Ptitsegradsky pond on river Torgoshe, Sergiev Posad district, 2005.

2 Methods

To select the optimal parameters of the tailwater's concrete fastening and assess its stability and strength, it is necessary to know the distribution of the total (averaged and pulsating) loads over the area of the fastening elements. In structures of the studied type, determining the pulsating component of the load can only be done experimentally. In the hydraulic laboratory of the Department of Hydraulic Structures, for several years, hydrodynamic studies of several short-span and low-point, respectively, open and closed culverts have been carried out [6-11]. In particular, a model of a three-point tubular spillway/outlet, made on a scale of 1:15 on an expanding (angle Θ changed in the range of $30^0...45^0$) outlet head of which innovative and standard designs of flow energy absorbers were installed, ensuring trouble-free pairing of pools with different schemes for maneuvering the gates of the culvert (Fig. 2).

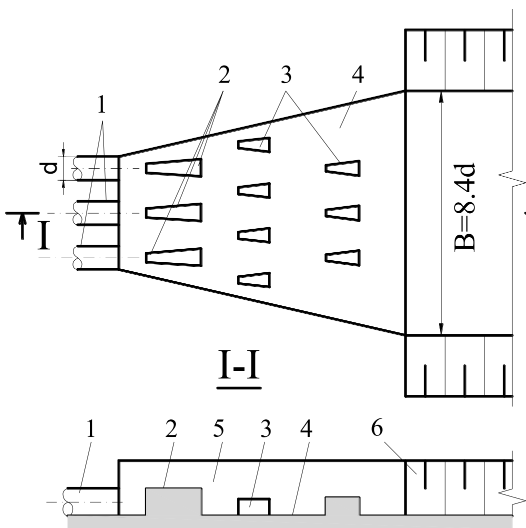


Fig. 2. Outlet head of three-point tubular culvert with triangular spreaders proposed by N.P. Rozanov: 1 is pipes; 2 is triangular spreaders of first row; 3 is triangular checkers; 4 is bottom of socket; 5 is postcard; 6 is discharge channel.

Experimental conditions: Reynolds criteria $(20...75)10^3$, head in the upstream (1...5) h_1, depth in the discharge channel h_2 = (0.5...2.4) h_1, flow energy in the outlet section of pipes $E_1 = (h_1 + V_1^2/2g) = (1.5...4.5)\ h_1$, where h_1 and V_1 – depth and average flow velocity at the outlet of the pipe, g - acceleration of gravity. To conduct hydrodynamic studies downstream on the expanding water body behind triangular spreaders, checkers, and on the apron, piezometers, and point inductive pressure pulsation sensors with a membrane diameter of 6 mm and a natural oscillation frequency in the water of 2 kHz were installed (about 80 pieces in total). The total load and overturning moments acting on the mounting plates were recorded by an areal sensor, the receiving plate of which corresponded to the dimensions of the plates under study, which is a removable platform corresponding in nature to plates 1.5x3 m and 1x1.5 m in size. The design of the three-component sensor plate made it possible to simultaneously measure vertical load and moments from longitudinal and transverse forces [12, 13]. The natural oscillation frequency of the sensor in water for the absorber of the first row was approximately 40 Hz, for the second row - 60 Hz, in air, respectively: 70 Hz and 90 Hz. Based on the records of pressure pulsation at the points of the water break and the apron, the maximum range of pressure pulsation ($2A_{max}$) was calculated, and then the standards P^1, under the assumption of normal distribution law.

The studies of the loads on the elements of the water break and the apron were carried out at a constant flow rate Q, varying on the model from 7 to 63 h/p, which corresponded to the energy parameter E_1 for three modes of conjugation in the downstream: bottom, surface and transient. At the same time, the coefficient of pipe flooding from the downstream side $\mathcal{E}_n = (h_1 - p)/h_2$, where p is the difference (the difference between the marks of the pipe bottom in the outlet section and the bottom of the discharge channel) for this design scheme of absorbers was equal to 0. In this case, the relative specific energy of the flow leaving the pipe with a diameter d was E_1/d = 1.5...4.5. Were taken 5...7 flow rates in the interval, covering the possibility of non-pressure and pressure operation of a tubular spillway or a small tubular transport crossing [14,16]. The determination of hydrodynamic loads was carried out both during the operation of the structure with the entire front and during the operation of the structure in the mode of the asymmetric opening of the gates.

3 Results and Discussion

The average pressure on the mounting plates from above for each hydraulic mode was determined by the height of the piezometric line above the bottom mark. A characteristic alternation of peaks and troughs was observed in the water hole, respectively, in front of and behind each absorber. Expectedly, the largest changes in the average pressure are observed in the water break behind the energy absorbers of the first row (Fig. 3a), significantly exceeding the downstream pressure, reaching up to $\overline{P_i}$= (0.5...2.0)γh_2. The largest relative pressure deficit $\beta = \Delta\overline{P_i}/(\gamma V_1^2/2g)$ occurs behind the first up to (β = 0.4) and after the last (up to β = 0.28) row of checkers.

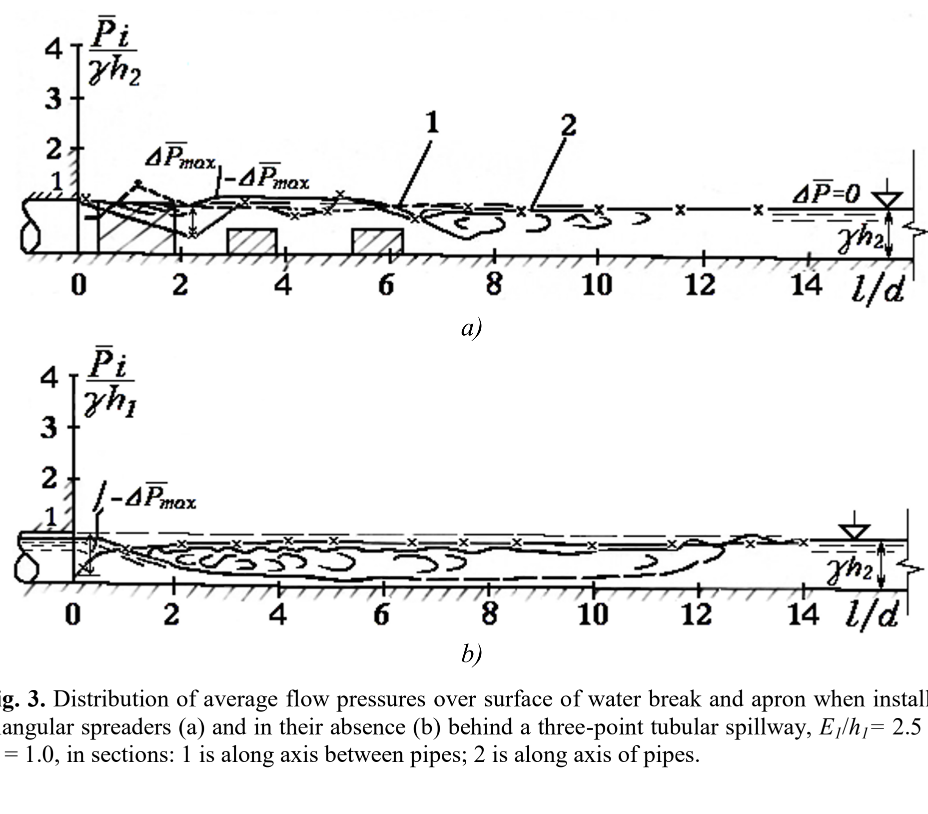


Fig. 3. Distribution of average flow pressures over surface of water break and apron when installing triangular spreaders (a) and in their absence (b) behind a three-point tubular spillway, E_1/h_1= 2.5 and $\mathcal{E}_n$= 1.0, in sections: 1 is along axis between pipes; 2 is along axis of pipes.

The absence of absorbers in the socket introduces a significant change not only in the parameters of the transition from one form of conjugation to another but also significantly affects the distribution pattern of the average pressure over the attachment area (Fig. 3b). The area directly behind the outlet section of the pipes, in the place of the compressed section β = 0.5 is exposed to the maximum pressure deficit. Moreover, the largest values of β correspond to the minimum degree of flooding of the jump, and with an increase in $\mathcal{E}_n$ from 1 to 2, they decrease by about 3 times, which was also noted by N.N. Belyashevsky for smooth water breakage of spillway dams [16,17]. With a smooth water break, the stability of the fastening plates is reduced by about 40%. The pressure drop $\Delta\overline{P}_l = (\overline{P}_l - \gamma h_2)$ tends to zero at $l \approx 16d$.

A change in the bell mouth angle Θ = $30^0 ... 46^0$ does not affect the nature of the longitudinal and transverse distribution diagrams of the average pressure in the socket and behind it. Taking into account all mentioned above, universal schemes of static loading with a vertical averaged load from the surface flow in the main sections of the fracture of the diagrams have been developed, where the numerical value of the pressure drops is determined by the nomograms $\pm\ \Delta\overline{P}_l/(\gamma V_1^2/2g) = f(E_1/h_1;\mathcal{E}_n)$, similar to determining the specific pulsation load, shown below in Figure 6.

In the absence of energy absorbers, the nature of the intensity distribution of pressure pulsation at the bottom of the water hole is identical to the data on the change in the standard of pressure pulsation in flat conditions, obtained by Vasiliev O.F., Lyatkher V.M., Ivoilov A.A., Yuditsky G.A. and some other researchers [15,16,17,19,20]. However, the presence of a significant expansion of the flow ($\Theta = 46^0$), which complicates its kinematic and turbulent structure, in comparison with flat conditions, leads to an increase in hydrodynamic pressure both in the waterway section (by 40%) and in the apron (by 60%). At the end of the apron, where the flow is close to uniform, the pulsation standard is about $0.01(\gamma V_1^2/2g)$ [17,19,20]. The maximum values of the P^1 pulsation standard are observed near the boundaries of the separation regions behind the spreaders (Fig. 4). When the parameter E_1/h_1 changes from 1.5 to 4.5, they are $(0.075...0.1)(\rho V_1^2/2)$, where – $\rho = \gamma/g$ is the density of water, γ is the volumetric weight of water. In the area of checker dampers, the value of P^1 reaches $0.065(\rho V_1^2/2)$. The maximum scatter of the measured values of the pulsation standards at points was also noted here. This indicates a complex local effect of absorbers on pressure fluctuations on the water-breaking plate.

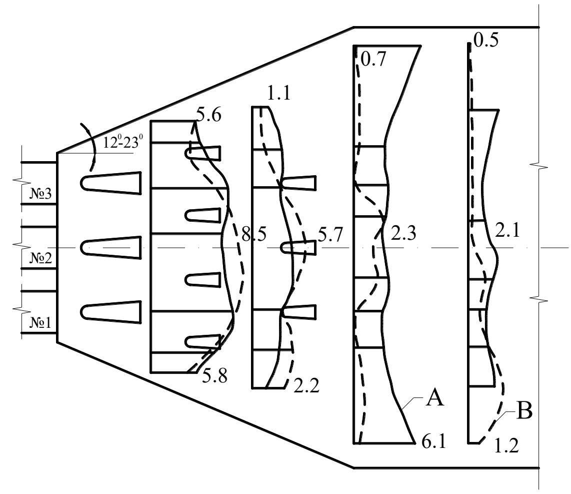


Fig. 4. Planned pattern of distribution of pressure pulsation standards $(2P^1/\rho V_1^2)10^2$ during operation of facility with E_1/h_1= 4.0 and $\mathcal{E}_n$= 1.0: – with all three pipes (A); - - - with two adjacent pipes (B).

The frequency characteristics of oscillations associated with the influence of mainly vertical mixing layers differ markedly from those usually observed under a plane jump at high Froude numbers. The prevailing oscillation frequency behind the absorbers is about 0.5 s^{-1}. It also provides the greatest contribution to the dispersion of oscillations. The oscillation spectrum is multicomponent. Correlations between pressure fluctuations at points drop down sharply across and along the flow.

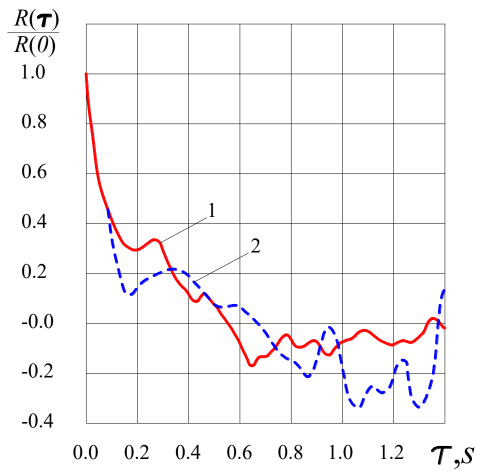
With different schemes for maneuvering gates of culverts, the change of hydraulic regimes at the water break for sections with the highest intensity of hydrodynamic action does not lead to a significant change in the distribution pattern of the pulsating pressure of the flow. However, with the transition to the regime with the asymmetric opening of the gates, the pulsation intensity at the water well increases, and it decays more slowly. Behind the socket on the apron at $h_2 \geq 1.25 h_1$, the nature of the flow is close to the surface. Therefore, the pressure pulsation standards are significantly lower than between dampers in the water well $P^I = 0.02(\rho V_1^2/2)$. Low-frequency components appear in the oscillation spectra, which are caused by oscillations of the free surface of the flow. The most energy-intensive pulsations have a frequency of 0.15 s^{-1}. In the water break behind the dampers of the first row, there is practically no surface roller, and the velocity gradients change significantly in depth; therefore, the lateral separation zones located in the annular regions and at the junctions with the vertical walls of the socket have a strong influence here.

In zones with maximum values of the pressure pulsation standard, the dominant frequencies are highlighted. In comparison with the rotation frequency of the roller above the jet $\omega_в$ according to the dependence proposed by V.M. Lather, at $\mathcal{E}_n < 1.2$ behind the absorbers of the first row showed a fairly good match (accuracy 4.8%) [15,18].

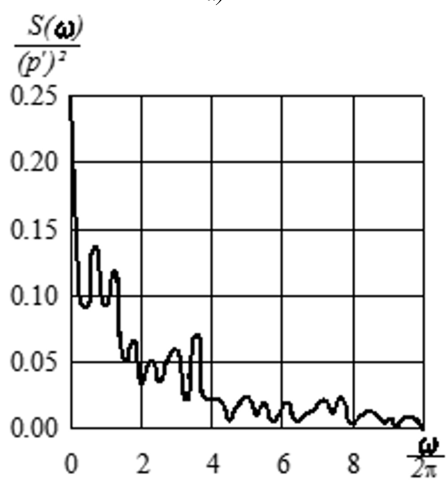
$$\omega_в \approx 2V/(h_2 - h_1) = (0.8...0.5)V_1/0.5\, L_в \qquad (1)$$

where V *is* the vertical component of the speed in the jump, $L_в$ is the length of the roller.

The prevailing frequencies of pressure fluctuations at the points of the surface of the water break behind the spreaders in the area of their influence are 0.3...3.8 Hz. Sensors far from the interfaces also register lower-frequency oscillations (Fig. 5a). The high intensity of pressure fluctuations at $\mathcal{E}_n = 1.5$ behind energy absorbers is explained by the approach of the vortex to the bottom and the presence of a highly sensitive component that significantly contributes to the total dispersion of pressure fluctuations in the initial sections of the jump. With the removal of the interface, as the jump approaches the second and then the third row of absorbers, the role of the low-frequency components increases. Upon transition to the surface mode of conjugation with the formation of a bottom roller, the mixing layer is removed from the bottom, and a low-frequency component appears in the spectrum of pressure fluctuations. On the apron, the spectra of point pulsations have an even lower frequency. The values of the prevailing frequencies fluctuate within 0.1 Hz. In the discharge channel and on the slopes, the pressure fluctuation occurs mainly due to surface disturbances; therefore, a low-frequency component is traced on the autocorrelation functions, which determines the spectrum's shape (Fig. 5b).



a)



b)

Fig. 5. Normalized autocorrelation functions (a) on apron and pressure fluctuation spectra (b) at bottom of water break of investigated tubular structure at $E_1 + p/h_1 = 4.5$ and $\mathcal{E}_n = 0.9$ behind the first row absorbers: 1 is along axis of the structure; 2 is along axis of outer pipe No. 3.

Therefore, a preliminary estimation of the frequencies of the maximum amplitude-frequency spectrum behind the triangular spreaders of the first row can be performed by designing and calculating the downstream elements according to the recommendations of V.M. Lather. For fastening plates located on the apron and in the discharge channel, the hydraulic regime that occurs when the structure is operated by two adjacent pipes turns out to be more difficult. The maximum values of the pressure pulsation standard P^1, in this case, are $0{,}07(\rho V_1^2/2)$. It should be noted that for three-point structures with a distance from the socket, the value of pressure pulsation decreases above the corresponding values for one- and two-point tubular structures by an average of 1.2...1.8 times, which is associated with non-identical interface conditions.

Based on the analysis of the processes of averaging the pressure fluctuations at points for different fastening sections behind the ameliorative three-point tubular structure, a set of graphical dependencies was developed to determine the standard of the specific vertical fluctuation load P^1_{Σ} and the load equivalent to the action of the overturning moment $P^1_{\Sigma M}$

with a known relative flow energy at the outlet of the pipe E_1/h_1 and flooding $\mathcal{E}_n$ (Fig. 6).

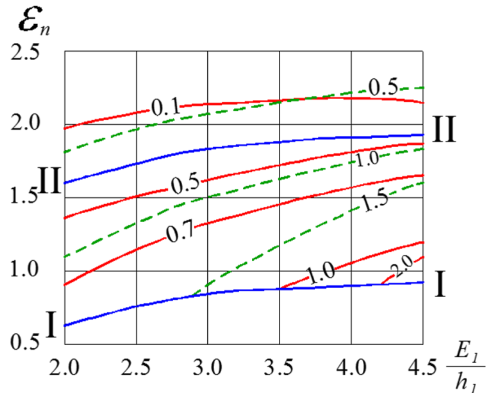


Fig. 6. Calculated values of specific pulsation load ($2.10^2\ P^I{}_{\Sigma}/\rho V_1{}^2$) and load equivalent to overturning moment ($2.10^2\ P^I{}_{\Sigma M}\ /\rho V_1{}^2$ - dashed curves) on apron plates behind outlet head: I-I and II-II - respectively, boundaries between zone of free spreading, hydraulic jump and faulty flow zone.

It has been experimentally proven that the construction of a quasi-static loading of plates by an instantaneous pulsating load for an expanding water break with triangular spreaders and checker-type dampers can be quite correctly used for longitudinal and transverse correlations corresponding to spatial turbulence and on an apron - homogeneous [7,14,18]. In this case, the drift rate of perturbations for the product of the transition from frequency to longitudinal spectra can be taken for triangular spreaders approximately 0.7, and in the initial sections of the apron behind the last row of absorbers and, accordingly, behind the output section of the bell – 0.2 ... 0.04 of the average flow velocity.

4 Conclusions

The conducted studies made it possible to establish the features of the change in the average pressure and the amplitude-frequency characteristics of the pressure pulsation at individual points of attachment downstream behind low-pointed tubular culverts with bell-shaped outlet heads and triangular energy absorbers on them, which are widespread in the Moscow region on ponds for reclamation and recreational purposes, playing an important role both in the arrangement and renovation of water bodies of the agro-industrial complex and in the construction or relining of small bridges and tubular crossings on highways. Graphical dependences were obtained that allowed determining the averaged and pulsating loads acting on the slabs of fastening of the water break and apron downstream of tubular spillways, which is the basis for choosing a rational design for fastening the downstream and calculating the optimal thickness of its reinforced concrete part within the boundaries of the influence of the expanding outlet head and in the discharge channel behind a three-point culvert. It is found that behind the socket under quasi-static loading of the plates by the actual pulsating load, it is possible to use the spatial correlation corresponding to homogeneous turbulence. The maximum values of the amplitude of the pulsating load on plates of any size should be calculated with a transition coefficient equal to approximately 3.85 for apron plates and no more than 4.5 for water breakage. A preliminary estimation of the frequencies of the maximum amplitude-frequency spectrum behind the triangular spreaders of the first row can be performed during the design and calculations of the downstream elements according to the recommendations of V.M. Lather for the roller under the jet.

Acknowledgments

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