Hydrodynamic Loads on the Water Chamber with Cavitating Dampers

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Abstract The data on the hydrodynamic loads on the water tank in the presence of cavitating non-erosion energy absorbers are presented.

It is shown that these loads increase in comparison with the cavitation-free regime, but despite this, the use of erosion-free dampers in the appropriate conditions is appropriate, different, providing favorable downstream conditions and reducing the volume of construction work and the cost of the structure.

As a result of cavitation and cavitation-erosion studies of erosion-free energy absorbers in vacuum-cavitation stands (in which simulations are carried out in compliance with gravitational similarity), moreover, for different stages of cavitation $\beta = K/K_{cr}$ ($K-$ cavitation parameter; $K_{cr}-$ its critical value characterizing the onset of cavitation), the drag coefficients C_x several types of erosion-free dampers (C_x—decreases with the development of cavitation β), the pulsation components of the horizontal hydrodynamic load on the damper, as well as the standards for the pulsations of the vertical hydrodynamic effects of the flow on the reservoir plate in the installation zone of the erosion-free dampers measured by "point" sensors $P' : \gamma v_1^2/2g$ (their maximum values are at $\beta \approx 0.5$, during supercavitation they decrease in comparison with those for the zero-cavitation regime), spectra and space–time transverse and longitudinal correlations of these pulsations.

Cavitation parameters were calculated according to the dependence

$$K = (H_{har} - H_{cr}) : \left(\frac{v_{har}^2}{2g}\right)$$

where $H_{char} = H_a + h$, (H_a—pressure above the free surface of the flow in the vacuum—cavitation stand, and for nature, atmospheric pressure; h—height of the water column above the damper; v_{har}—the characteristic speed of the flow on the damper, which was taken from the diagram of the velocity distribution in front of the damper at the level of the damper top; g—acceleration of free fall; v_1—velocity

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in a compressed section with a depth h_1 in front of the damper (the experiments were carried out with the outflow of water from under the shutter).

Keywords Cavitation parameters · Hydraulic structures · Cavitation erosion · Energy absorbers · Pulsation loads

1 Introduction

This article is devoted to one, relatively small issue of the dynamics of hydraulic structures—the determination of the hydrodynamic loads on the slabs of a high-pressure spillway in a cavitating flow in the presence of erosion-free dampers.

While working on the implementation of this research, the author simultaneously studied in the laboratory pulsating loads on real structures—elements of the downstream spillway devices of the projected lower Kafirnigansky hydrosystem.

In connection with the intensive construction of high-pressure and medium-pressure hydroelectric systems in mountainous areas, the spillways of which operate at high flow rates, a very urgent task is to develop reliable and economical downstream devices that provide intensive energy extinguishing with favorable uninterrupted flow regimes and the absence of cavitation erosion of streamlined elements. Traditional methods—stilling wells and walls do not always provide a solution to the problem. In a number of cases, they are additionally satisfied with elements as energy absorbers, which are an effective means of dealing with malfunctioning currents. However, most of the used types of absorbers have a serious drawback—they are destroyed in cavitation conditions.

Cavitation research N. P. Rozanov and his students (R. M. Razakov, A. T. Kaveshnikov, N. N. Rozanova) made it possible, on the basis of experiments, to develop several types of erosion-free or close to erosion-free dampers and obtain dependencies for determining the hydrodynamic loads on them at various stages of cavitation [1–3]. This made it possible to use energy absorbers at high flow rates, which was carried out at the spillways of the Shamkhor and Artyomov hydroelectric complexes.

At the same time, it should be noted that in cavitation studies carried out until recently, the effects of cavitation on energy absorbers were considered only from the point of view of the possibility of an erosion hazard and the effects of the flow on the absorbers themselves. There is no doubt, however, that the degree of development of cavitation affects the characteristics of the pressure pulsation in the cavitating flow not only on the surface of the dampers but also on the water tank. In cavitation-free modes, the pulsation loads on the water chamber have been studied in some detail for some types of absorbers, as for the loads on the water chamber under cavitation modes and erosion-free absorbers, they have not been studied. If we take into account that the cost of downstream attachment devices for high-pressure structures can be 20–30% of the cost of the entire structure, then it becomes obvious how important it is to correctly design the downstream device in order to ensure their long-term reliable operation. This is also required in the presence of erosion-free energy absorbers, which are promising, since they expand the scope of energy absorbers—devices that prevent unfavorable malfunctioning currents in the downstream. The main direction of this article is the study of hydrodynamic loads on slabs of a water face in the presence of erosion-free energy absorbers on it in conditions of various stages of cavitation and in its absence.

1.1 Hydrodynamic Effects of the Flow on the Fastening Elements in the Downstream in the Absence of Cavitation

Investigations of pressure pulsations in a hydraulic jump in the absence of cavitation are of interest mainly to the flow, which, in our opinion, allows us to draw a number of significant general conclusions.

Currently, two main approaches to the study of pressure pulsations have been outlined.

1. With the help of "point" sensors that register the pressure pulsation at individual points of the element surface and the propagation of its area by specifying multidimensional probability distribution functions and multidimensional correlation functions.
2. With the help of total sensors that directly measure the total load or moment on the investigated element.

The pressure pulsation measured by point sensors cannot be directly used to determine the load on a large area due to the lack of synchronicity of pulsations at individual points of the streamlined surface [4–8].

It should be noted that in all studies, conclusions were drawn about the possibility of modeling pressure pulsations if the Froude similarity criterion is met. In addition, the authors determined the lowest self-similarity zone, which corresponds to the Reynolds number $Re_m > (5 - 10) \cdot 10^3$. The conclusions made in these works substantiate the conduct of pressure pulsation studies in laboratory conditions on small-scale models. This undoubtedly expands the possibilities of the experiment for a better solution of the problems of hydrodynamic loads for specific objects.

1.2 Consequences Caused by the Action of Cavitation

The experience of operating high-pressure hydroelectric complexes shows that the force of the dynamic interaction of the flow and the elements of the downstream can lead to severe damage to the latter. These damages can be of two types: firstly, erosive from the action of cavitation, or, secondly, due to an increase in pulsating loads in the cavitation mode. The use of erosion-free absorbers, in principle, removes the issue of cavitation erosion of both absorbers and slabs. However, it should be borne in mind that the experience of the practical application of such structures is not yet great, therefore, it is necessary to exercise some caution in their design. When using erosion-free dampers, it is sometimes suggested to use solid walls in places where vertical vortices of cavitation torches can occur. In the event that individual cavitating vortices nevertheless break through to the surface of the pond, they should be made of materials with high cavitation resistance [5]. As for damages associated with an increase in hydrodynamic loads due to cavitation, it is not possible to avoid them by changing the design of cavitating absorbers. Failure to consider these loads can lead to serious damage downstream.

1.3 Feed Effects on the Elements of Hydraulic Structures in the Presence of Cavitation

As far as we know, the question of the wobble of cavitation on the pulsation characteristics of the flow acting on the slabs of the reservoir during the cavitation flow has not been practically studied. However, a qualitative understanding of the pressure pulsations behind the dampers can be obtained by the example of works studying various kinds of obstacles (protrusions, gates, etc.), since both are essentially sources of pressure pulsations.

In work [2, 6], laboratory tests of a flat valve operating under high-speed flow conditions with a head up to 200 m were carried out. One of the aspects of the work was to study the dynamic effect of a cavitating flow on the valve. According to the authors, the values of the pressure pulsation standards at the gate in the presence of developed cavitation are twice the values of the standards in its absence. In the supercavitation mode, data are also not given because the author of the work failed to obtain supercavitation.

In the works of V. M. Lyatkhera and L. V. Smirnov [2, 3, 5, 9–14] obtained data on the characteristics of pressure pulsation, according to which there is an increase in dispersion and a significant deformation of the pulsation spectrum towards high frequencies as cavitation develops. In the separation zone, the spectrum changes during cavitation, naturally, due to the fact that the most intense pulsations occur in the presence of cavitation.

In the first in hydraulic engineering, the force effects of a cavitating flow on erosion-free dampers were studied by N. N. Rozanov [15–19] based on cavitation studies, the author of the work managed to obtain quantitative regularities of horizontal averaged and pulsating loads as cavitation develops. In the course of the experiments, a decrease in drag coefficients with the development of cavitation was recorded. The noted decrease in the drag coefficient during cavitation, especially under the conditions of developing stages and supercavitation, the author of the work explains by the fact that with the development of cavitation the character of the pressure distribution curves on the streamlined body changes [20].

At the second stage, the author studies the pulsation loads on the damper at the maximum range. The analysis of the research results showed that when the absorbers operate in conditions of cavitation (initial and developed), an increase in the instantaneous pulsation component of the load occurs in comparison with the non-cavitation mode. For example, in non-cavitation mode, the ripple coefficient δ_p constant and equal to 0.14, and at the developed stage ($\beta = 0.5$) $\delta_p = 0.65$, that is, it increased by 4.6 times, and at $\beta < 0.5$ there is a tendency to decrease it.

2 Methods

To obtain data on the conditions of occurrence, development and impact of cavitating flow on the elements of spillway hydraulic structures, vacuum stands are used. Their main advantage lies in the fact that they allow for the creation of cavitation conditions on models that meet the Froude similarity criterion.

Studies of the force effects of the flow in the presence of cavitation were carried out in the vacuum test bench of the laboratory of hydraulic structures of the Moscow State Medical Institute.

The vacuum unit allows conducting cavitation studies of hydraulic structures elements in the presence of a free flow surface. The rather large dimensions of the installation provide for cavitation studies of flat and half-space models of sufficiently large dimensions, with direct observation of cavitation on absorbers located in a hydraulic jump.

It is known that when simulating the operation of energy absorbers in the downstream in the presence of cavitation and in its absence, it is necessary to observe the Froude similarity criterion (Fr = idem) and to carry out research in the self-similar region at Reynolds number $Re_m > Re_{gr}$.

To observe the approximate similarity of cavitation phenomena, the following conditions must be met:

$$K_n = \eta K_m$$

where $K_n \, and \, K_m$—parameters of cavitation for nature and model; η—correction factor of the model (we take $\eta = 1.0$ considering the large scale of the model $Re_m = 10^5 - 10^6$).

A hydraulic jump in the installation was created when water flowed out from under the shutter with a sharp loud sound.

The fragmentary model was a pond with two rows of damping devices: in the first row—erosion-free dampers, in the second—a pond wall.

The studies used the following instruments:

- Piezometers—to determine the average pressure and the bottom of the reservoir;
- Sensor–plate—for measuring the total vertical and moment loads in the longitudinal and transverse directions.

3 Results and Discussion

Averaged pressures were obtained (Fig. 1) $\frac{\overline{P_1}}{\gamma v_1^2/2g}$ at the bottom of the reservoir (in the cavitation-free mode) and the values of the standards of specific pulsation loads $P_v^{'} : \frac{\gamma v_1^2}{2g}$ and overturning moments $P_m^{'} : \frac{\gamma v_1^2}{2g}$ on a stilling slab at its different relative lengths $L : h_1$ (Fig. 2). The values of these ripple loads were obtained using a special sensor plate. They, like the values of $P^{'} : \frac{\gamma v_1^2}{2g}$ varied in depending on the value of β and were maximum at the developed stage of cavitation with $\beta \approx 0.5$ and during supercavitation they became less than in the non-cavitation mode. The specified sensor had a natural frequency in water of about 100 Hz.

As expected, a decrease in the relative length of the slab $L : h_1$ lead to an increase in the standard of pulsation of specific loads (Fig. 2); but for "point" sensors, they were obtained even more significant (for example, when $\beta = 0.5$ $P^{'} : \frac{\gamma v_1^2}{2g} \approx 0.3$—with a damper of the same type). The specific pulsation load on the slab with cavitating dampers, measured by areal sensors, turned out to be 22–28% more than the load according to the data of "point" sensors. With regard to one of the high-pressure hydroelectric complexes [6] at $v_1 = 24\mathrm{m/sec}$ the volumes of concrete required for the downstream construction were calculated for the variants with a stilling well and with erosion-free dampers. In the latter version, the volume of concrete turned out to be 1.5–1.6 times less. In addition, in this version, the issues of preventing unfavorable malfunctioning currents in the downstream [1, 2, 4] were well resolved.

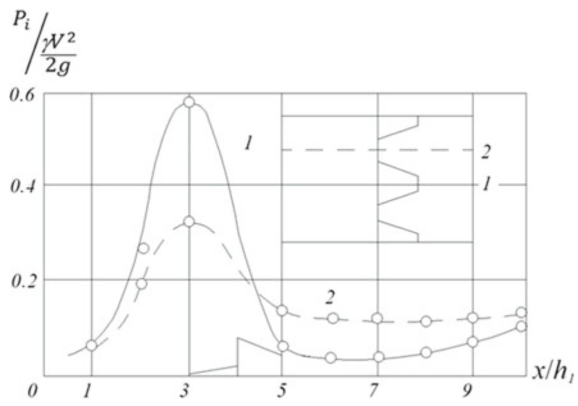

Fig. 1 Averaged pressures at the bottom of the water hole of erosion-free dampers 2 in sections 1 and 2 (jump flooding coefficient n = 1.0)

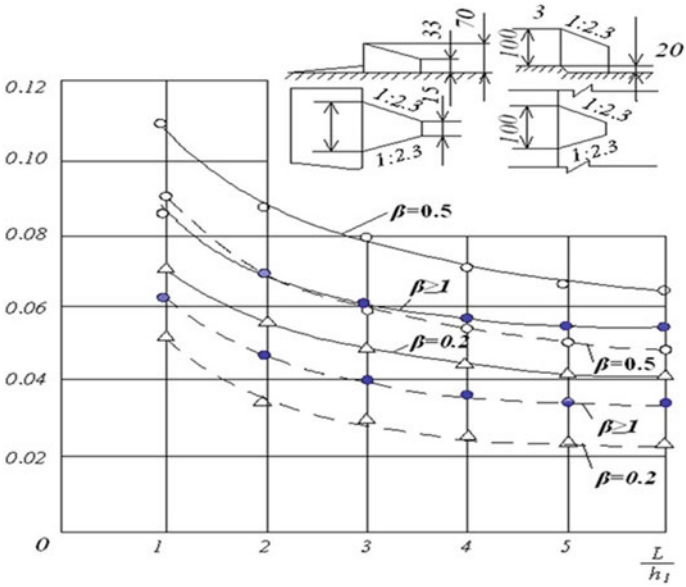

Fig. 2 Vertical detached loads *(1)* and loads equivalent *(2)* to the action of the tipping moment depending on the relative length of the plates $L{:}\ h_1$ and the cavitation stage $\beta = K{:}\ K_{cr}$ for absorbers *2* and *3*

4 Conclusions

1. For several types of erosion-free energy absorbers, data were obtained on the averaged and pulsating vertical and horizontal loads on the absorbers and the slab, which makes it possible to carry out the required strength and stability calculations of the elements of the downstream devices.
2. Studies have shown that despite a slight decrease in the energy absorbing capacity of the absorbers during the development of cavitation (decrease in C_x) and an increase during cavitation of absorbers of the pulsation effects of the flow on the absorbers and the water column, in appropriate conditions they are rational, providing more favorable operating conditions for the downstream and reducing the volume of construction work and construction cost.

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