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# Hydrodynamic effects on the flow elements of the downstream devices in the presence of cavitation

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**Abstract.** The use of “erosion-free” energy absorbers operating during cavitation without the formation of cavitation erosion extends the use of energy absorbers and diffusers at high flow rates, removing or reducing cavitation restrictions. Considering that energy absorbers are effective means of preventing dangerous malfunctioning currents in the downstream, they make it possible to increase the water level and reduce the cost of fastening the downstream. Give the opportunity to expand the scope of their application should be taken into account when designing. Dampers of this type were used at the spillways of the Shamkhor and Artyom waterworks.

## 1. Introduction

This work is devoted to one, relatively small issue of the dynamics of hydraulic structures - the determination of hydrodynamic loads on the slabs of a high-pressure spillway in a cavitating flow in the presence of erosion-free energy absorbers. In connection with the intensive construction in mountainous areas of high and medium-pressure hydroelectric systems, the spillways of which operate at high flow rates, a very urgent task is to develop reliable and economical downstream devices that provide intensive extinguishing of the flow energy in the downstream under favorable uninterrupted flow regimes and the absence of cavitation erosion of streamlined elements.

Traditional methods of extinguishing energy with the help of stilling wells and walls do not always provide a solution to the task. In some cases, such elements as energy absorbers are additionally satisfied, 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 prof. 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 to obtain dependencies for determining hydrodynamic loads on them at various stages of cavitation. 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 cavitation development affects the characteristics of pressure pulsation in the cavitating flow not only on the surface of the dampers, but also on the water tank.

In non-cavitation modes, the pulsation loads on the water chamber have been studied in detail for some types of absorbers, as for the loads on the water column under cavitation modes and erosion-free absorbers, they have not been studied.

If we take into account that the cost of devices, downstream attachments for high-pressure structures can be 20 ... 30% of the cost of the entire structure, it becomes obvious how important it is to correctly design the downstream devices 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 work is the study of hydrodynamic loads on the slabs of the water face in the presence of erosion-free energy absorbers on it in the conditions of various stages of cavitation and in its absence.

The experience of operating high-pressure hydroelectric systems shows that due to the dynamic interaction of the flow and the downstream elements, very serious damage to the latter can occur. 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. It should be borne in mind that the experience of the practical application of such structures is still not 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 cavitation flares can occur. In cases where individual cavitating vortices nevertheless break through to the surface of the pond, they should be made of materials with high cavitation resistance [1–5]. As for the damage 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 take into account the specified loads can lead to serious damage downstream.

Significant pulsating loads, especially when the elements of spillway structures operate in a cavitation mode, destroy the metal linings of concrete surfaces. It can be assumed that a pulsating load causes fatigue in the anchorage of the cladding, and rupture of the anchors leads to the destruction of the cladding is observed behind the slots of the gates, on absorbers and in other separation zones [6–9].

The lining of the absorbers was torn off at the Gatun hydroelectric complex. Two rows of cubic absorbers with a height of 2.75 m are installed on the water side of the hydroelectric complex for better flow spreading. The front edge of the dampers is lined with steel sheet 76 mm thick to avoid abrasive wear. As a result of examinations, cavitation destruction of the side faces of the absorbers was found, and during repair they were covered with steel sheets 50 mm thick. Repeated examinations showed that the cladding was torn off from the lateral faces, and erosion at the tearing points reached even greater dimensions.

The dynamic operation of steel linings, as we see it, to a large extent depends on the frequency composition of the hydrodynamic load. A steel cladding, anchored to the concrete, can be thought of as a plurality of “plates” supported at points. Such a system is known to have many degrees of freedom that allow the "plates" to vibrate in many of their own forms, which negatively affects the strength of the facing.

With the development of cavitation, the spectrum of hydrodynamic loads is very wide, there is every reason to assume the presence of stable resonant vibrations of the lining, leading to high stresses in its elements, as well as to a fatigue phenomenon, the result of which is the destruction of fasteners. The assumption can be confirmed by the results of experimental work [9–18]. The vibration of a thin

($\delta$ = 5 mm) steel plate embedded along the contour in a cavitating liquid flow was investigated Plates with dimensions $bxl$=400x800 $\text{мм}^2$ replaced a part of the upper wall of the working chamber of the experimental stand. The flow in the chamber, remaining in the formations of the vortex area due to the flow around the flat valve installed at the inlet The relative constraint of the inlet section was $a/h$=0.8 (a- opening the shutter; $h$ – camera height). In the experiments, the absolute pressure in the chamber was varied. The corresponding cavitation numbers were $\sigma$=2.45; 0.8; 0.07. Variations in the elongation of the upper fibers of the slab were recorded. The load cell was positioned in the middle of the slab and embedding the original side.

During the experiments, pressure pulsations were recorded at points on the upper wall of the chamber. On the oscillogram $\sigma$ = 2.45, forced and resonant vibrations of the low-frequency slab are traced. With a decrease in the average pressure in the flow $\sigma$ = 0.8 high-frequency bursts appear, indicating the beginning of oscillations of higher tones. When the pressure in the flow drops even below σ = 0.07, a typical cavitation condition is observed. The pressure deviations are very high frequency. The stove enters the mode of continuous resonant vibrations at high tones. It is interesting to compare the graphs of the change in the load intensity and the elongation of the fibers of the slab. Where $P_0'$ and $\mathcal{E}_0'$ are calculated under the assumption that the load is proportional to the velocity head. It was found that although in the regime with c $\sigma$ = 0.07 the rms value of pressure fluctuations relatively supplies, the intensity of dynamic stresses is significantly (~ 3 times) higher than in the regime with $\sigma$ = 2.45.

Thus, the work shows that the strength of thin elastic linings depends to a large extent on the actual ratios of natural and disturbing frequencies.

As a rule, fractures associated with an increase in hydrodynamic loads due to cavitation phenomena also cause erosional destruction, when structures are not erosion-free. The latter can also be observed in places subject to abrasive wear. This kind of phenomenon occurred at the Bhakra, Sauselie, San Esteban, Navaye and Trinity, Denison, Anderson Ranch, Norfolk waterworks and at the Krasnoyarsk waterworks [14].

These facts clearly show the consequences of not taking into account the cavitation characteristics of extinguishing devices. In all these cases, the primary cause is the increased turbulence of the flow and the associated cavitation that occurs when the flow around the absorber is separated.

The most accessible and reliable method for studying the interaction of a turbulent flow with structures under cavitation conditions, in our opinion, is the method of model studies. The studies carried out at present, carried out on cavitation stands in laboratory conditions, show good agreement between the results obtained and the data of field observations. As an example, we can cite the works of N.P. Rozanov, R.M. Rozanov and N.T. Kaveshnikov [19–23], in which comparison of model and full-scale cavitation characteristics is given. These works contain rich material about various forms of cavitation on all possible types of absorbers. The authors also determined the ability of absorbers to cause erosion at various stages of cavitation development. Comparisons of the zones of destruction on absorbers and reservoirs obtained on a large-scale model - in a vacuum installation with areas of cavitation destruction corresponding to full-scale structures show that model cavitation studies give satisfactory results when transferred to nature, not only at the onset of cavitation, but also in depth erosion [1, 2, 21, 24, 25]. Comparison of cavitation parameters for elements of natural structures damaged by cavitation erosion with critical parameters of cavitation on the model show that they are in nature 2 ... 3 times lower than the model $K_{cr}$, which in turn means that destruction from cavitation in natural conditions occurs at the stages of cavitation $\beta = \frac{K}{K_{cr}} = 0.4 - 0.6$ that is, in the developed stage of cavitation.

In our opinion, the main attention should be paid to the study of the force effects of the flow in the developed stage of cavitation, since in this case, as the literature data show, for non-erosional structures of the downstream elements, the greatest destructive effects of cavitation are observed.

## 2. Methods

### *2.1. Experimental technique Vacuum installation, models and similarity criterion.*

Various cavitation units are used to reproduce cavitation and study its effect on the elements of hydraulic structures. These installations, according to the principle of their operation, can be divided into vacuum benches and hydrodynamic tubes [26]. Hydrodynamic tubes provide tests that are closest to full-scale conditions. In modern hydrodynamic tubes, the flow rates are close to the speeds of full-scale structures, and in some cases even exceed them. To excite cavitation in the working chamber, bluff bodies, waves imitating a defect in the surface of irregularities, a tapering Venturi-type chamber, and others are installed. Such installations, differing only in structural elements, have been created and are successfully operating in different laboratories, for example, at the VNIIG named after B.E. Vedenov, SKB Mosgidrostal, NIS Hydroproekt, MISS, MGMI and other organizations. The main disadvantages of hydrodynamic tubes are the small dimensions of the working chamber and the absence of a hydraulic jump.

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 is that they allow the creation of cavitation conditions on models that meet the Froude similarity criteria. The working chamber of the cavitation stand should be of sufficient size to accommodate large models and should provide for the reproduction of sections of structures with a free water surface. In the working chamber of these trays, a reduced pressure must be maintained in accordance with the scale of the models, despite the low speeds in the working chamber, the pumping equipment of the vacuum stand must be designed for relatively high costs.

The research was carried out in the vacuum test bench of the laboratory of hydraulic structures of the MGMI.

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 conduct research in the self-similar region at Reynolds numbers.

$$Re_m > Re_{gr} \qquad (1)$$

The experiments were carried out at Froude numbers calculated for a compressed section $Fr_1 = 16 - 64$ and Reynolds numbers $Re_1 = 4 \cdot 10^5 - 1.1 \cdot 10^6$.

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

$$K_n = \eta K_m \qquad (2)$$

$K_n\ and\ K_m -$ parameters of cavitation for nature and model, $\eta -$ the correction factor for the model scale was taken as $\eta \approx 1.0$ given the large scale of the model $Re_1 = 10^5 - 10^6$.

The absence of cavitation will be ensured provided

$$K > K_{cr} \qquad (3)$$

The cavitation parameter is usually written in the following form:

$$K = \frac{H_{har} - H_{cr}}{v_{har}^2 / 2g} \qquad (4)$$

where: $H_{har} = H_a + h$ ($H_a -$ pressure created above the articulated surface in a cavitation unit, m. height of the water column, for nature - atmospheric pressure); $h -$ height of the water column under the damper, m. w.c; $v_{har} -$ characteristic flow velocity (taken from the velocity distribution diagram at the level of the damper top), m/s; g – free fall acceleration, $h_{cr} -$ pressure $m/s^2$; (in m, w.c.) steam formation (taken as for pure water).

*2.1.1. In experiments, cavitation in its various stages was created by adjusting the vacuum.*
The hydraulic jump in the installation was caused by the outflow of water from under the shutter with a sharp blast. The fragmentary model is a pond with two rows of damping devices: in the first row - erosion-free dampers, in the second - pond wall (Fig. 1). Four types of absorbers in Fig. 2 were investigated, with measurement of pulsation and averaged pressures at points, and a stand with erosion-free absorbers with measurement of hydrodynamic vertical loads on the slab of the stand for horizontal - on absorbers of various types.

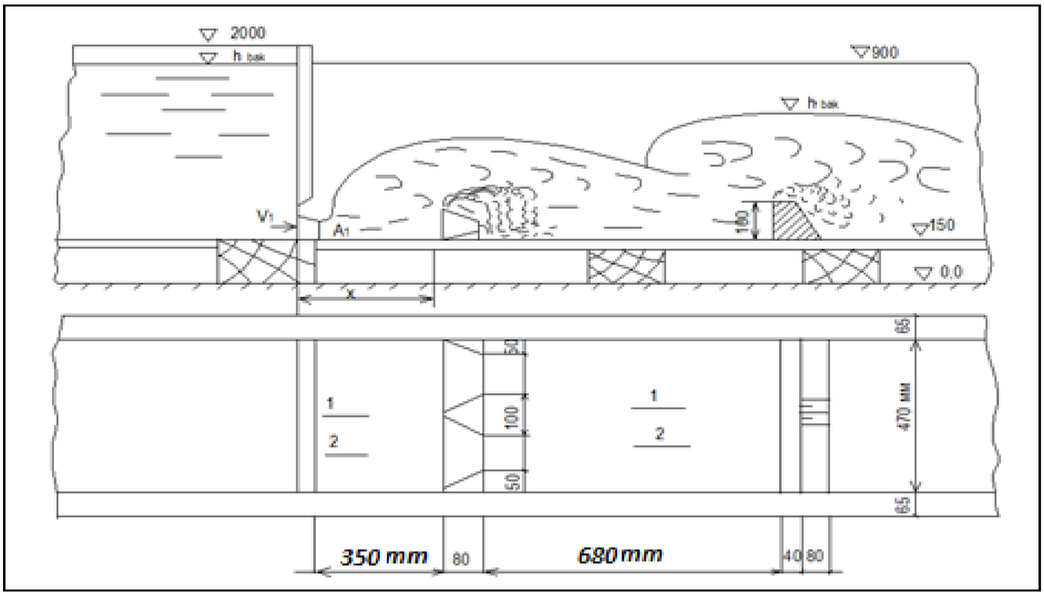


**Figure 1.** Diagram of a fragment of a water face in a cavitation stand: 1-1 section of measurements of hydrodynamic parameters between the dampers; 2-2, the same for dampers

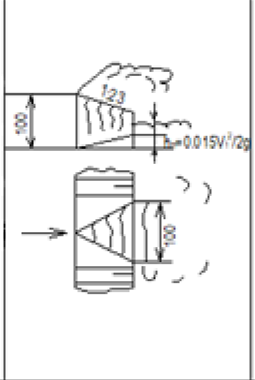
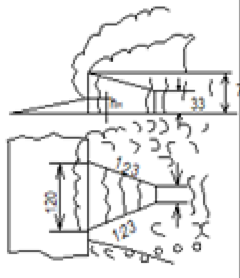
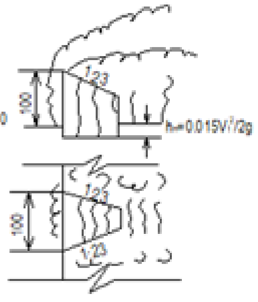
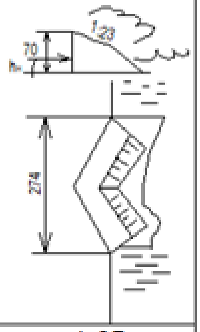
| № | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Damper shape |  |  |  |  |
| Kф | 0.8 | 1.75 | 1.90 | 1.05 |
| C₀ | 0.6 | 0.98 | 1.0 | 0.85 |

**Figure 2.** Study of the shape of model erosion-free energy absorbers (dimensions in mm)

The drag coefficient was used as a dimensionless characteristic of the averaged component of the absorber's response

$$C_{cav} = \frac{\overline{P_g}}{\gamma \omega_g v_{nab}^2/2g} \qquad (5)$$

The unknown parameters$\overline{P_g}$ and $v_{nab}-$ in expression (4) were determined experimentally. The average drag force of the damper $\overline{P_g}$ measured with a horizontal force sensor. The evaluation of the horizontal component of the reaction of the absorber $P_g'$ was carried out according to the value of the root-mean-square deviation of the pulsation of the forceful action of the flow on the investigated structures. The process was recorded using the indicated sensor - plate. As a result of data processing, the dependences of the pressure pulsation standards on the absorbers on the cavitation stage were obtained.

The following instruments were used in the studies:

- Pitot tube - for measuring average velocities in non-cavitation mode;
- piezometers - to determine the averaged pressure at the bottom of the pond;
- an inductive type pressure sensor with a receiving membrane diameter of 13 mm, for measuring the pulsation pressure component;
- sensor - plate - for measuring total vertical and moment loads;
- sensor - plate - for measuring the average and pulsation component of the horizontal load.

The onset of cavitation was determined visually with stroboscopic lighting. The obtained values of $K_{cr}-$ for erosion-free dampers practically coincide with the results [1–5], [26].

## 3. Results and Discussion

3.1. *Results of experimental studies. Averaged pressures on the slab at the pond.* To assess the stability and strength of slabs, it is necessary to know the average piezometric pressure, or rather, its deficit, that is, the difference between the pressures above and below the slab.

Averaged pressures were measured using piezometers measuring piezometric heads over the area of the water face. The main attention was paid to the study of the averaged pressures along sections № 1 and № 2, that is, along the lines passing through the absorbers and between them (Fig. 1).

When the downstream is operated with dampers, pressure redistribution along the length of the water basin is observed. At the same time, the coefficient of pressure unevenness, for example, for points in front of the dampers and behind them, can reach ten. This indicates that the installation of absorbers introduces very noticeable resistance to flow. In both cases, the pressure maxima are observed in the zone in front of the absorbers, and their greatest value is confined to section № 1, that is, directly in front of the absorbers. The averaged pressures between the dampers are less, for example, for damper № 2 this decrease was about two. In the zones behind the absorbers, the opposite picture is observed - the pressure along the section through the absorbers is lower than the pressures along the line between them. For all types of absorbers under study, the distribution of averaged pressures is approximately the same and differs practically only in the amplitudes in the zones in front of the absorbers.

In figures 3 and 4 it can be seen that the magnitude of these amplitudes increases with an increase in the absorber's resistance coefficient. So for the damper № 1 ($C_0 = 0.6$) the average pressure referred to the pressure head is $\frac{\bar{P}}{\gamma v_1^2/2g} = 0.4$, and for the damper № 3($C_0 = 1.0$) $\frac{\bar{P}}{\gamma v_1^2/2g} = 0.62$.

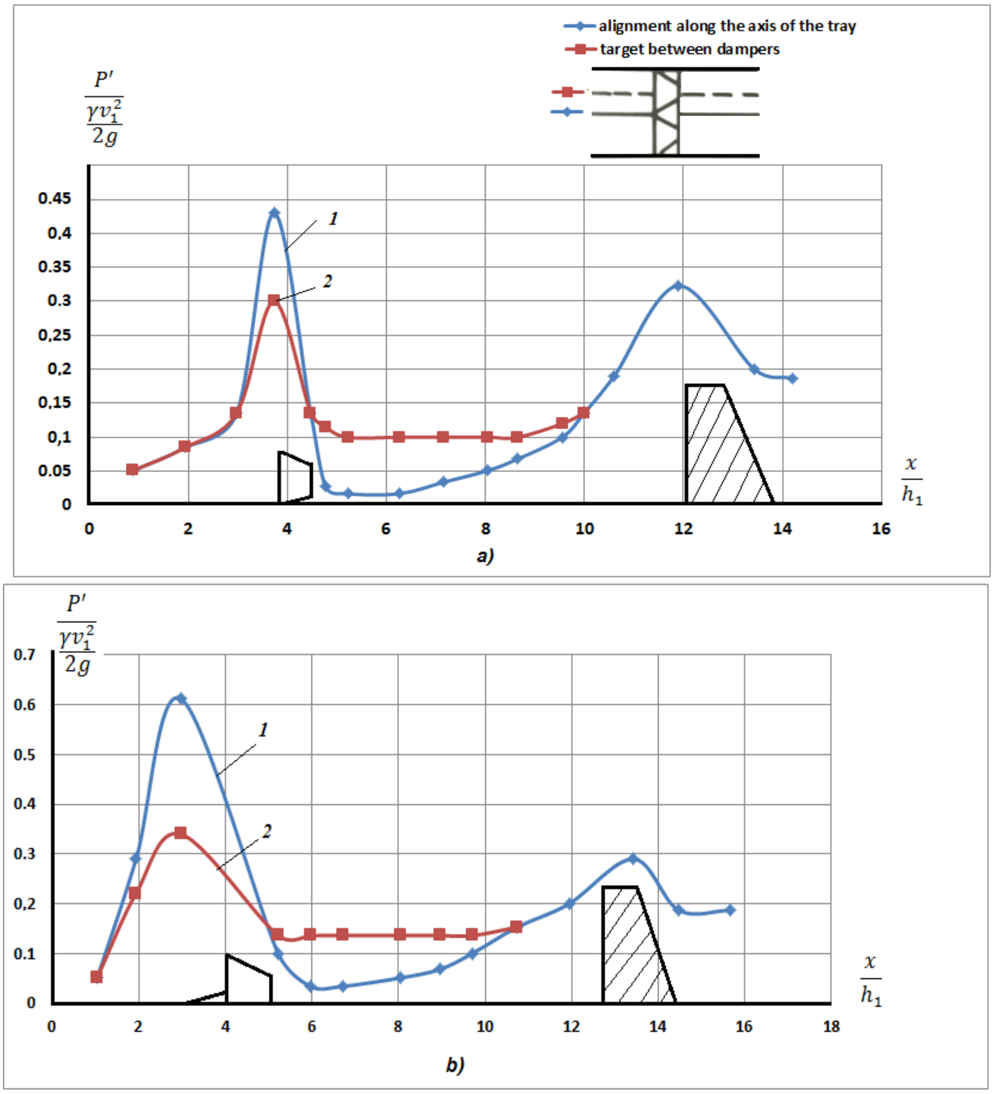


**Figure 3.** Average pressures at the bottom of the pond with erosion-free dampers: a – for the damper № 1; b – for erosion-free damper

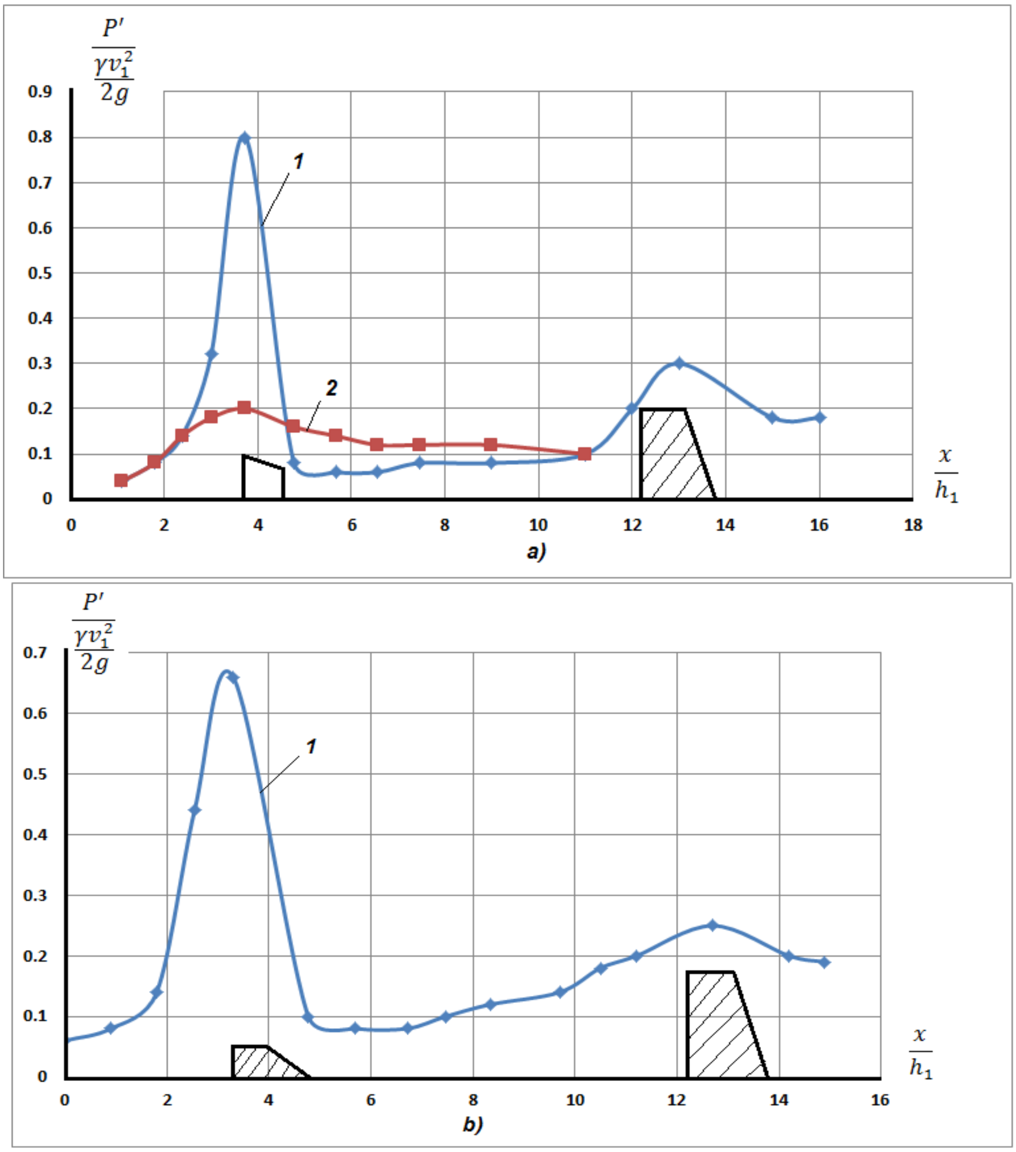


**Figure 4.** Average pressures at the bottom of the pond of erosionless absorbers № 3, № 4

It is a certain fact that the development of averaged and pulsation pressures occur in opposite phases. For example, even in a non-cavitation mode after the damper, the piezometric head related to the velocity head is 0.03, and the pulsation standard is 0.12, that is, the pulsation pressure behind the dampers is 4 times higher than the static one. In the developed stage of cavitation, this ratio increases by about 8 times. In front of the dampers, the reverse can be considered - the static pressure increases and the hydrodynamic pressure decreases by about 5 times, regardless of the stage of cavitation.

In conclusion, it should be noted that the research results allow us to judge the distribution of static loads on the slab.

## 4. Conclusions

1. The vacuum test bench and the sensitivity of the equipment used in this work make it possible to carry out experiments on a fairly large scale of the model. The relatively small width of the stand, 0.6 m, seems to impose limitations on volumetric models.

2. Cavitation erosion of absorbers and slabs of the water face is a fairly common type of destruction of the downstream attachment elements of high-pressure structures, therefore the most promising absorbers should be considered erosion-free cavitation plumes that do not close at the solid boundaries of the structure.

3. Universal plots obtained as a result of studying the distribution of the averaged pressure on the slab of the reservoir with cavitating erosion-free absorbers make it possible to construct a calculated plot of the total averaged vertical pressure component depending on the type of energy absorbers and the location of the considered section. Energy absorbers for the water face redistribute the averaged loads on the water face plates (increasing them in front of the absorbers and decreasing them behind them).

4. Studies have shown that the distribution law of the total averaged vertical load practically does not depend on the type of absorbers, while its amplitude values are different, especially in the area where the latter are installed. Moreover, there is a clear tendency to increase the load in front of the absorbers with an increase in the absorber's resistance coefficient. For example, for an absorber with c $\mathrm{C}_0 = 0.6$ $\overline{P_i}/\gamma v_1^2/2g = 0.4$, а для гасителя $\mathrm{C}_0 = 1.0$ this relationship is equal 0.62.

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