Hydrodynamic loads on a water drain with cavitation quenchers

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Abstract. The data on the hydrodynamic loads on the water body in the presence of cavitating energy without erosive dampers on it are presented. It is shown that these loads increase in comparison with the non-cavitation mode, but, despite this, the use without cavitation dampers in appropriate conditions is advisable, providing favorable downstream regimes and reducing the volume of construction work and the cost of construction. It is proved that for multiple types without erosive energy absorbers, data were obtained on the averaged and pulsating vertical and horizontal loads on the absorbers and the slaughter plate, which allows us to carry out the required calculations of the strength and stability of the elements of the downstream devices. As a result of cavitation and cavitation studies of erosion-free energy absorbers in cavitation stands, coefficients of any resistance \( C_x \) of several types of aerosol-free absorbers were obtained; as well as pulsation standards measured by "point" sensors for the vertical hydrodynamic effects of the flow on the water culvert in the installation zone of an erosion-free damper.

1. Introduction
It is devoted to one relatively small issue of the dynamics of hydraulic structures – the determination of hydrodynamic loads on slabs of a high-pressure spillway under a cavitating flow in the presence of erosion-free energy absorbers. In connection with the intensive construction of high- and medium-pressure head waterworks in mountainous areas, spillways that operate at high flow rates, a very urgent task is to develop reliable and economical downstream devices that provide intensive damping of flow energy in the downstream with favorable uninterrupted flow patterns and the absence of cavitation erosion of streamlined elements. Traditional methods - quenching energy with the help of water wells and walls do not always provide a solution to the problem. In some cases, elements such as energy absorbers, which are an effective means of combating faulty flows, additionally suit. However, most of the types of absorbers used are inherently serious – they are destroyed by cavitation. Cavitation studies prof. Rozanova N.P. and his students allowed, 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 were carried out at the spillways of the Shamkhor and Artyomovsk hydroelectric facilities[1–4].

At the same time, it should be noted that in cavitation studies, cavitation on energy absorbers was considered only from the point of view of the possibility of 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 pressure pulsations in the cavitating flow not only on the surface of the quenchers but also on the water body. In cavitation-free regimes, the pulsating loads on the water body have been studied in sufficient detail for some types of absorbers, and as for the loads on the water surface under cavitation modes and erosion – free dampers, they have not been studied. If we take into account that the cost of downstream fixture devices 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 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 field of application of energy absorbers - devices that can prevent adverse malfunctioning flows in the downstream. The main direction of this article is the study of the hydrodynamic loads on the slabs of the water culvert in the presence of erosion-free energy absorbers on it under conditions of various stages of cavitation and its absence.

The operational experience of high-pressure hydraulic units 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, erosion from the action of cavitation or secondly due to an increase in pulsating loads in the cavitation mode. The use of erosion-free dampers, in principle, removes the issue of cavitation erosion of both dampers and slabs. It should, however, be borne in mind that the practical experience in using such structures is not great, therefore, some caution must be exercised in their design. When using erosion-free dampers, it is sometimes suggested to use solid walls in places where vertical cavitation torches may occur. If individual cavitating vortices nevertheless break through to the surface of the water hole, they should be made of materials with high cavitation resistance [5–9]. As for the damage associated with an increase in hydrodynamic loads due to cavitation, it is not possible to avoid them by changing the designs of cavitating dampers. Failure to do so may result in serious downstream damage.

Significant ripple loads, especially when the elements of the spillway structures are in cavitation mode, are the cause of the destruction of the metal cladding of concrete surfaces. It can be assumed that the pulsating in magnitude load causes a fatigue phenomenon in the anchor fastening, and the rupture of the anchors leads to the destruction of the lining. Often, tearing of the lining is observed behind the grooves of the shutters, on the dampers, and in other separation zones [10–12].

Separation of the damper lining took place at the Gatun hydroelectric complex [2]. Two rows of cube-type dampers with a height of 2.75 m are installed on the waterworks of the waterworks for better flow spreading. The frontal face of the dampers is faced with a 76 mm thick steel sheet to prevent abrasion. As a result of the surveys, cavitation fractures of the side faces of the absorbers were found and during repair, they were covered with steel sheets 50 mm thick. Repeated examinations showed that the lining from the side faces was torn off, and erosion at the separation sites reached even larger sizes.

The dynamic work of steel cladding, as it seems to us, largely depends on the frequency composition of the hydrodynamic load. Steel cladding attached to concrete with anchors can be imagined as a multitude of “plates” supported at points. Such a system, as is known, has many degrees of freedom, which allow the “plates” to oscillate in many of their forms, which negatively affects the strength of the lining [13].

With the development of cavitation, the spectrum of hydrodynamic loads is very wide and there is every reason to assume the presence of stable resonant vibrations of the cladding, leading to high stresses in its elements, as well as to fatigue phenomena, the results of which are the destruction of fasteners. The assumption can be confirmed by the experimental results [11, 12]. Fine vibrations were investigated (δ= 5 mm), embedded in the contour of a steel plate in a cavitating fluid flow. Slabs in size in plan b * ℓ=400*800 mm² replaced part of the upper wall of the working chamber of the experimental stand. The flow in the chamber while remaining pressure was accompanied by the formation of a whirlpool due to the flow around the flat shutter installed at the inlet. The relative constraint of the input section was equal to a/h=0.8 (a - opening the shutter; h- camera height).
In the experiments, the absolute pressure in the chamber was varied. The corresponding numbers in cavitation were $\delta = 2.45; 0.8; 0.7$. The vibrations of elongations of the upper fibers of the plate were recorded. The strain gauge was located in the middle of the plate and the seal on the long side.

Records of pressure pulsations at points of the upper chamber wall are obtained. The oscillogram shows the forced and resonant vibrations of a low-frequency plate. With a decrease in the averaged pressure, high-frequency bursts appear in the flow, indicating the beginning of oscillations of higher tones. When the pressure in the flow drops even lower ($\delta = 0.07$), a pressure pulsation typical of the cavitation condition is observed. Pressure deviations are very high frequency. The plate falls into the mode of undamped resonant vibrations at high tones.

It is interesting to compare the graphs of changes in load intensities and elongations of the fiber of the plate. Here $P'$ and $E'$ are calculated in the sentence that the load is proportional to the pressure head. Although in the mode with $\delta = 0.07$ the rms value of the pressure fluctuations decreases relatively, the intensity of dynamic stresses is significantly (~3 times) higher than in the mode with $\delta = 2.45$. Thus, this work shows that the strength of thin elastic linings to a large extent depends on real ratios of natural and disturbing frequencies.

As a rule, damage associated with an increase in hydrodynamic loads due to cavitation phenomena also causes erosion damage when the structures are not erosion–free the latter can also be observed in places subjected to abrasive wear. Such phenomena occurred at the waterworks of Bhakra, Sauselier, San Esteban, Navai, and Trinity, Denison, Andersen-Ranch, Norfolk, and at the water spillway of the construction spillways of the Krasnoyarsk waterworks. The described examples are especially typical for high-pressure structures operating in cavitation conditions. Widely known, for example, the destruction of the quenchers Bonneville, Norfolk, and Gatun. A similar bibliography is therefore given to the issue in [14].

These facts clearly show what consequences the neglect of the cavitation characteristics of extinguishing devices can lead to. In all these cases, the root cause of the damage was the increased turbulence of the flow and the cavitation associated with it, which occurs during the detached flow around the damper.

The most accessible and reliable method for studying the interaction of a turbulent flow with a structure under cavitation conditions, as we see it, is the method of model studies. Currently conducted studies performed on cavitation stands in laboratory conditions show a good agreement between the results and field observations. As an example, the work of prof. N.P. Rozanova [3], in which comparisons of model and natural cavitation characteristics are given. These works contain rich material on various forms of cavitation on various types of absorbers.

The authors also determined the ability of dampers to cause erosion at various stages of cavitation development. Comparisons of the destruction zones on absorbers and water holes 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 beginning of cavitation but also in terms of erosion depth. Comparison of cavitation parameters for elements of field structures damaged by cavitation erosion with critical parameters of cavitation on the model shows that they are in the kind below the model $K_c$ in $2…3$ times, which in turn means that destruction from cavitation under natural conditions at the stages of cavitation $\beta = K/K_c = 0.4..0.6$, that is, in the developed stage of cavitation.

2. Methods
To reproduce cavitation and study its effect on the elements of hydraulic structures, various cavitation installations are used. In hydraulic engineering, hydrodynamic pipes and vacuum stands are mainly used.
Hydrodynamic pipes provide the tests closest to the natural conditions. In modern hydrodynamic pipes, flow rates approach the velocities of full-scale structures, and in some cases even exceed them to excite cavitation, poorly streamlined bodies, waves imitating a surface irregularity defect, narrowing chambers such as Venturi and others are installed in the working chamber. The main disadvantage of hydrodynamic pipes is the small size 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 drainage hydraulic structures, vacuum stands are used. Their main advantage is that they allow the creation of cavitation conditions on models that meet the criteria of similarity of labor.

The working chamber of the cavitation stand should be large enough to accommodate large models and should include the reproduction of sections of structures with a free surface of the water. In the working chamber of these trays, reduced pressure must be maintained in accordance with the scale of the models. Despite the small speeds in the working chamber, the pumping equipment of the vacuum stand must be designed for relatively high costs. The vacuum cavitation test bench for hydraulic structures was first implemented at the proposal of N.P. Rozanova [4], in the NIS Hydroproject in 1960. The stand is equipped with vacuum pumps, allowing to achieve a vacuum of up to 9.8 m. water consumption in the model can reach 500 l/s. Such installations are currently successfully used in VNIIG them. B.E. Vedeneeva, NIS Hydroproject, and MGMI. At these stands, cavitation studies of the waterworks of the Sayano-Shushensky, Athashinsky, Bukhtarminsky, May, Shamkhor, Bartogaysky, Nizhne-Kafirnigansky and other high-pressure hydraulic units operating under cavitation conditions were conducted. Studies of the force effects of the flow in the presence of cavitation were carried out in a vacuum stand of the laboratory of hydraulic structures of the Moscow Agricultural Academy named after K.M. Timiryazev.

3. Results and Discussion
The use of “erosive” energy absorbers operating during cavitation without the formation of cavitation erosion spreads the application of energy absorbers and spreads at high flow rates, removing or reducing cavitation restrictions.

Considering that energy absorbers are effective in preventing dangerous interruptions in the downstream, they can increase the waterhole mark and reduce the cost of attaching the downstream, the possibility of expanding their scope should be taken into account when designing. This type of damper was used at the spillways of the Shamkara and Artyomovsk hydroelectric facilities [9].

As a result of cavitation and cavitation-erosion studies [15–20] erosion-free energy absorbers in vacuum-cavitation stands (in which modeling is carried out in compliance with gravitational similarity), and for different stages of cavitation $\beta = K: K_{cr}$ ($K$ – cavitation parameter; $K_{cr}$ – its critical value, characterizing the beginning of cavitation), coefficients of any resistance $C_{r}$ of several types of non-erosive dampers are obtained ($C_{r}$ decreases with the development of cavitation, that is, with a decrease in $\beta$), the pulsation components of the horizontal hydrodynamic load on the state; as well as pulsation standards measured by "point" sensors for the vertical hydrodynamic effects of the flow on the water culvert plate in the area where the erosion-free damper is installed $P' : \gamma \theta^2 / 2g$ (their maximum values are at $\beta=0.5$, during supercavitation, they decrease compared with those for the non-cavitation mode), as well as the obtained spectra and spatio-temporal transverse and longitudinal correlations of these pulsations. Cavitation parameters were calculated according to the dependence $k = (H_{char} - H_{cr}) : (\theta^2_{char} / 2g)$, here, $H_{char}$ = $H_a + h$, $H_a$-pressure above the free surface of the flow in a vacuum-cavitation stand, and for nature - atmospheric pressure; $h$ is the height of the water column above the quencher; $\theta_{char}$ – the “characteristic” rate of bending of the flow onto the damper, which was taken from the velocity distribution diagram in front of the damper at the level of the damper’s top; $g$ – acceleration of gravity; $\theta_{char}$ – speed in a compressed flow with depth; $h_c$ - in front of the quencher (experiments were carried out at the outflow of water from the sub-gate). Averaged pressures were also obtained (figure 1)
$P_i; \gamma \Delta \phi^2/2g$ to the bottom of the water hole (without cavitation mode) and the value of the specific pulsation load standards $P'_i; \gamma \Delta \phi^2/2g$ and of tumbling moments $P''_i; \gamma \Delta \phi^2/2g$ on a water plate with its various relative lengths $L; h_i$, (figure 2). The value of these ripple loads were obtained using a special plate – a sensor. They, like the values of $P'; \gamma \Delta \phi^2/2g$, varied from depending on the magnitude $\beta$ and were maximum during the advanced stage of cavitation with $\beta \approx 0.5$, and with supercavitation, they became smaller than with no cavitation mode. The specified sensor had its frequency in the water of about 100 Hz, which is approximately an order of magnitude higher than the measured frequencies.

**Figure 1.** Averaged pressures at the bottom of the water hole of erosion-free dampers 2 in sections 1 and 2 (jump flooding coefficient $n = 1.0$)
As expected, a decrease in the relative length of the slab $L/h$ leads to an increase in the standards of pulsations of specific loads (figure 2); by the “point” sensor, they were obtained even more significant (for example, with $\beta \approx 0.5$, $P' = \gamma \theta^2 / 2g \approx 0.3$ – with a damper of the same type). The specific pulsating load on the slab with cavitating cavities without erosive dampers, measured by areal sensors, turned out to be 22...28% more load according to the “point” sensors.

Concerning one of the high-pressure hydroelectric facilities with $\vartheta_r = 24 \text{ m/s}$ the concrete volumes necessary for the downstream installation were calculated for versions with water well and without erosive dampers. In the latter embodiment, the volume of concrete turned out to be 1.5 – 1.6 times less. Moreover, in this variant, the issues of preventing adverse faulty currents in the downstream were well resolved.

4. Conclusions

- For fiscal types without erosive energy absorbers, data were obtained on the averaged and pulsating vertical and horizontal loads on the absorbers and the slaughter plate, which allows us to carry out the required calculations of the strength and stability of the elements of the downstream devices.
- Studies have shown that in spite of some decreases in the energy-absorbing capacity of dampers during the development of cavitation (a decrease in $C_x$) and increases in cavitation of dampers, the pulsating effects of the flow on the dampers and the water body, under appropriate conditions, they are rational, providing favorable operating conditions for the downstream and reducing the volume of construction work and cost of construction.
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