Numerous publications are devoted to the problem of energy dissipation in the case of increased roughness. Their results are generalized in monographs [1-3]. An examination of these works and comparison of the conditions of energy dissipation in the case of considerable roughness of various structures – chutes, fishways, stepped spillways – indicate that the operating conditions of the last have a number of specific features whose revelation requires setting up special experimental studies.

The construction of dams made with steps has been known for at least 1500 years [4]. The construction of dams with stepped faces from a technological viewpoint was convenient at the time when dams were made of stonework. Such dams were used as spillways for passage of unit discharges up to 2-3 m²/sec. Even a century ago concrete spillway dams of this type were made with a stone facing (Goulburn weir in Australia [5]). In the first half of the 20th century stepped spillways were made of ordinary concrete (Van Rhynveld dam in South Africa with a height of about 35 m [1] and New Croton dam [6]).

The heightened interest in stepped spillways in recent years is related to the development of the technology of constructing dams of roller compacted concrete. A general analysis of the characteristics of constructed stepped spillways shows the following:

- stepped spillways of various heights, from 10 to 90 m, are used for passage of surplus water discharges;
- the unit waste discharges of such dams reach 30 m²/sec; modern dams with a height of at least 30 m are used for passage of unit discharges of more than 10 m²/sec, and their spillway heads are made streamlined. The slope of the downstream face of these dams is 0.6-0.8;
- such spillway dams, as a rule, are made without gates on the crest, unregulated;
- the height of the steps of dams made of rollcrete, which is proportional to the thickness of its layers, varies within 0.3-1 m;
- stepped spillways of a trapezoidal profile are intended for passage of small unit discharges (up to 5 m²/sec); their height is up to 10 m, and in individual cases about 20 m, and the slope of their spillway face is made more gentle than that of dams with streamlined crest heads.

Many publications concerning the flow conditions of stepped spillways have appeared in the past 10-15 years. A number of them examine the results of investigations of specific structures, make generalizations, and some give only their general description [6-13]. Other works give the results of studying the flow conditions within the limits of stepped spillways; various flow regimes and limits of their change are examined; hydraulic head losses or the values of velocities at the foot of the spillways, limits of occurrence of aeration of the flow, and its effect on head losses are determined [4, 14-21].

In the present work we will dwell only on an examination of the flow conditions of stepped spillways with streamlined crest heads, on a general description of the flow regimes within these spillways, and on a determination of the depths and head losses mainly for the case when the flow on the spillway did not lose continuity.

**Experimental Device and Method of Estimating Head Losses on a Stepped Spillway Face.**

**Arrangement of Spillway Face.** The experimental device for studying the working conditions of stepped spillways was placed in a stationary 15-m-long hydraulic flume (Fig. 1). The water discharges on the experimental device were measured by a sharp-crested weir, the upper and lower pool levels were determined by point gauges. The water depths on the spillway face were established in the following way: at the end of the horizontal treads of the steps the distance from their bottom to the free surface of the flow was measured; profiles of the free surface of the water were constructed, and already from these profiles the depths were established in planes orthogonal to the surface passing through the edges of the steps.

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Fig. 1. Schematic diagram of experimental device: I) wood head; II) metal sheet – upstream face of dam; III) stepped part of dam made of organic glass; IV) section of constant width. Dimensions in millimeters.

Head losses within the limits of the stepped spillway were determined by two methods. The values of the hydraulic friction coefficient $\lambda_R$ were calculated on the basis of the depths determined in the way indicated above on a section with an approximately constant depth. The total energy losses on the spillway face were also determined from the value of the velocity coefficient $\varphi$. The experiments were conducted for discharges on the model up to 185 liters/sec in the range of Reynolds numbers 12,000-300,000. In the case of a high roughness the flow regime in this range of Reynolds numbers is self-similar. Friction of the smoother side walls of the model spillway was not taken into account when calculating the coefficient $\lambda_R$. The error of such a calculation even for maximum experimental values of the discharges does not exceed 4%.

Determination of coefficient $\lambda_R$ is possible if the depth of the water in the contracted section at the foot of the spillway is known. Owing to considerable fluctuations of the free surface of the flow and in a number of cases owing to its substantial disintegration, this characteristic of the flow during direct measurements is established with a significant error. A more reliable indirect method was used for determining this depth. By means of regulating devices located at the end of the flume, a hydraulic jump was realized in the contracted section at the foot of the dam. The first conjugate (contracted) depth was calculated from the measured depth of the lower pool, which is the second conjugate depth and is established with an acceptable accuracy. A similar method of estimation was used at the B. E. Vedeneev All-Russian Hydraulic Engineering Institute (VNIIG) (A. N. Rakhmanov and M. E. Faktorovich) and by the authors of [9, 20] in investigations of stepped spillways.

Coefficient $\lambda_R$ was estimated in a narrow range of unit discharges from 8 to 20 liters/dm·sec, when at the site of the edges of several adjacent steps the water depths differed by not more than 5%. In the case of large discharges uniform motion was observed on the entire length of the spillway, and in the case of small discharges the flow splashed intensely. The velocity coefficient $\varphi$ was established for the entire range of discharges, including its small values for which the flow lost continuity.

Two variants of a spillway with streamlined heads and slopes of the downstream face of 1.25 and 0.8 were investigated in the present work (Fig. 2). Models of a dam of different heights – 4.54, 8.29, and 11.53 dm – were examined for the latter variant. The longitudinal outline of the spillway head was made according to Creager coordinates with a profiling head $H_{pr} = 3$ dm, in the experiments the head on the spillway crest did not exceed 3.15 dm. A line passing through the edges of the steps was taken as the profile. The upper curved part of the dam profile was assumed smooth within the vertical distance, which was not more than $(0.2-0.3)H_{pr}$. On the curved section of the model spillway most steps were made with a smaller height than on the straight section of the profile. The height of the steps in the initial section was $2/3$ and $0.5$ of the height of the steps on the remaining length. Such a relation of the sizes of the steps corresponds to rolling the dam respectively in three or two layers on each of the main steps and in two and one layers on the curved section of the profile. Transition sections with steps of a smaller height than on the remaining section of the spillway were provided for below the smooth spillway head on a number of constructed dams: 11 steps were made on the La Puebla de Cazalla dam [11], five on the Monksville [6], and 10 on the M'Bali [12].

The conditions and character of the flow on the stepped spillway face change substantially depending on the value of the unit discharge, the limits of the change in the flow regimes to some extent depend on the size of the steps and slope of the downstream face. The data of a number of investigators and our experiments indicate the following general picture of their working conditions.