Overflowing phreatic dams built with the use of modern composite materials

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Abstract. Costs and terms of hydroelectric complexes construction, of low pressure constructions in particular, can be significantly reduced by ensuring the safe passage of flood discharge through the crest of water-retaining structures. When water-retaining structures are made from soils, this condition can only be fulfilled by creating special fastenings of a crest and dam slopes from erosion. There is a large number of technical solutions for overflowing phreatic dams construction with the use of stone, concrete, reinforced concrete and metal. However, most of them have specific disadvantages. They are high materials consumption, labour input and expenses. These disadvantages, in our opinion, can be minimized by applying modern composite materials such as geosynthetic shells, concrete-filled textile floor-floor-mats and coarse-pored concrete. The paper describes structures of overflowing phreatic dams invented by the authors with the use of modern composite materials, as well as the results of model hydraulic studies of overflowing phreatic dams with a downstream slopes formed by geosynthetic shells.

1 Introduction

Phreatic dams were the most widespread water retaining structures at small hydroelectric complexes. Their advantages are the use of local building materials, reliability, and the use of integrated mechanization of technological erection processes, short construction time and low cost. Passage of flood discharge through the crest of phreatic dam in most cases is the most economical and technological solution, since it allows you to refuse the construction of expensive water retaining structures. However, without the implementation of special structural solutions to create fastenings of the crest and slopes protecting them from erosion, flood discharge overflow through a phreatic dam is not permissible.

The existing structures analysis of low-pressure phreatic overflow dams [1-3] showed significant drawbacks in them: either a strongly spread profile of the dam is required when fastening the slope with a stone, or it is very laborious in the case of crib fasteners, or require the use of expensive elements (for example, reinforced concrete slabs) . In recent years, structures using composite materials such as geosynthetic shells, concrete-filled

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textile floor-floor-mats and coarse-pored concrete have become widely used in hydraulic engineering.

Geosynthetic shells are relatively new composite materials for hydraulic engineering. In national construction, these constructions became popular only in the last decade. They look like some containers of synthetic woven or non-woven material, providing the possibility of filling them with soil or some other material. Air-and water-permeable geotextiles are used to make geosynthetic shells. Shells filling as a rule is carried out through inlet hoses by dredgers in the form of pulp, while water is discharged through the water-permeable surface of the shell. At present, geosynthetic shells are widely used in hydraulic engineering while constructing bank fortifications, dams, dikes, and man-made hydraulic territories.

Concrete-filled textile floor-mat is a composite material consisting of two high-strength woven materials connected by flexible tie-spreaders; the space between them is filled with a self-compacting concrete mixture on the construction site. By varying the length of the spread, they can be made in thickness range of 5 to 60 cm. The floor-floor-mats can be constant or variable in thickness, permeable to water and not. Concrete-filled floor-floor-mats are used as fastenings of soil slopes on canals, dams and banks of rivers and lakes.

Coarse pored concrete is a composite material obtained from a mixture of dense gravel or crushed stone, binder and water. The absence of sand in the mixture and the limited consumption of cement determine large-pore structure of the concrete, its air and water permeability, reduced weight. Coarse-pored concrete refers to rolled concrete, the distinctive features of which are high intensity of concrete works; significant reduction of construction time; low labor costs due to all technological operations mechanization and the use of high-performance machinery. Nowadays, coarse-pored concrete is used to create impervious devices, drains, filtering spillways.

The construction experience using these composite materials shows their designs to have low cost and high manufacturability of the device, and this fact provides a significant economic effect [4]. At the same time, the possibility of using modern composite materials as protective coating for the crest and slopes of overflowing phreatic dam has not been sufficiently studied.

Thus, the effective structures development of overflowing phreatic dams using modern composite materials, as well as the research of operating conditions of such structures is a modern and up to date problem.

2 Materials and Methods

A large number of different technical solutions for crest and slopes fastening of overflowing phreatic dams and methods of their investigation are known. The most ancient ones are constructions with stone use. Such constructive solutions, in our opinion, were sufficiently reliable, but not technological and therefore led to a significant rise in dams cost. Perfection of fastening constructions of phreatic overflowing dams with stone use led to the following: crib structures fastenings; mesh structures fastenings; joint grounding fastening of the stone top layer with concrete or reinforced concrete. These improved designs have made it possible to increase the permissible unit discharge for them up to q = 20-25 m^2/s. The disadvantage of the involved structures is considered to be significant increase in labor input and expenses of their construction.

The design solution developed by P.I. Gordienko in 1960s allowed to increase rates of discharge passed over the dam. He proposed a phreatic dam, which includes a spillway nose on monolithic reinforced concrete crest and a downstream slope protected by prefabricated reinforced concrete slabs of wedge shape having drain holes in thin part [5]. Such dam construction allowed the flow of unit discharge to be up to 60 m^2/s. However, it also had significant drawbacks: in order to ensure a stable conjugation mode of races, a very gentle downstream slope was necessary (from 1: 6 to 1:10).

The overflowing phreatic dam design, proposed by P.I. Gordienko, was improved by Yu.P. Pravdivets, who proposed the end section of the spillway slope to be performed in the form of a bucket deflector on bedrock and a bucket plunge race on non-rocky bed [5]. Due to this fact, the downstream slope laying of the overflowing phreatic dam began to depend only on the strength soil properties of the dam body. In our opinion, the use of expensive elements made from prefabricated reinforced concrete, as well as high requirements for their manufacturing and installation quality, and implementation of a reverse filter under the slabs are the disadvantages of such overflowing phreatic dam.

In the United States, the most distributed overflowing phreatic dams are the ones with a device on the downstream slope of water collecting channel in the form of a stepped rolled concrete spillway [5]. The main advantage of this design is production high rate. Drain holes are made in fastenings to let the filtration water flow, and the end section of the downstream slope fastening is lowered below the downstream channel mark in order to prevent erosion.

Overflowing phreatic dam calculations includes calculations made for dumby phreatic dams (verification of local and general slope stability, filtration calculations, etc.), as well as a number of additional calculations related to discharge pass by overflowing through the crest. Additional calculations can be divided into two groups: 1 group - hydraulic calculations; 2 group - deformation and strength calculations of fastenings.

The most important parameters of the first group are: passed computed discharge, head on the crest and the flow depth within the downstream slope, the quenching degree of flow excessive kinetic energy, and also the conditions for hydraulic flow regime change within the downstream slope and the conditions of flow conjugation in the tail race. In most cases, the calculations of the first group are based on the results of experimental studies of physical models of overflowing dams, since they give the most reliable results about hydraulic parameters of the flow passed through the dam.

Many authors note that in order to increase the reliability and economic efficiency of overflowing phreatic dams, it is necessary to make downstream face with increased roughness, in particular of stepped outline. This makes it possible to provide a significant quenching of excessive kinetic energy of discharged stream within the downstream slope, also to facilitate fastening of tail race and to reduce the cost of dam construction [5].

Based on the analysis of overflowing phreatic dams structures and methods for their calculation, the following technical solutions were developed using modern composite materials, such as geosynthetic shells, concrete-filled textile floor-floor-mats and coarse-pored concrete [6].

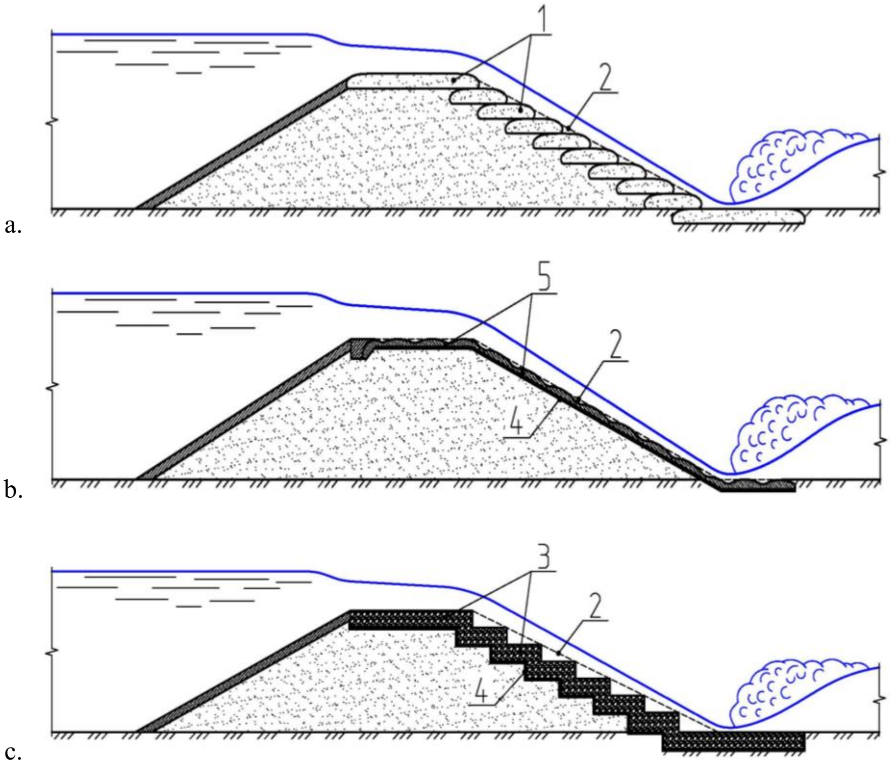


Fig. 1. The proposed structures of overflowing phreatic dams: a. with geosynthetic shells; b. with concrete-filled textile floor-floor-mats; c. with coarse-pored concrete; 1 - geosynthetic shells; 2 - smooth downstream slope; 3 - coarse-pored concrete; 4 - geotextile filter; 5 - concrete-filled textile floor-floor-mats.

The overflowing phreatic dam with a downstream slope made from geosynthetic shells (Figure 1, a) has the following features:

- phreatic dam within the crest and downstream slope is fastened by geosynthetic shells filled with local non-rock soil;
- geosynthetic shells laying is carried out with overlapping of upper rows on lower ones, creating steps within the downstream slope, the outer edge of which fits into smooth form of the downstream slope.

When using concrete-filled textile floor-mats (Figure 1, b), the phreatic dam is fastened with floor-mats filled with self-compacting concrete within the crest and the downstream slope. To fasten the crest and slopes it is suggested to use concrete-filled textile floor-mats with variable thickness and filtration holes, such as Incomat FP, Incomat Flex or Incomat Crib made by Huesker Synthetic GmbH Company.

Coarse-pored concrete is proposed to be placed within the crest and the downstream slope, analogous to the experience of rolled concrete placing, with the formation of stepped or step-curved downstream slope (Figure 1, c). The advantages of a coarse-pored concrete construction in relation to a rolled concrete one are the following: simplification of downstream slope fastening construction, due to the absence of making additional drainage holes; efficiency quenching increase of excessive kinetic energy of discharged flow within the downstream slope, which is ensured by passing a part of water discharge in concrete pores and by collision of outflowing filtration stream from the concrete with the discharged overflowing along the downstream slope by the flow.

To justify the reliability of overflowing phreatic dams development done by the author's, special model and full-scale studies are required, as well as the development of appropriate design techniques taking into account their construction features.

3 Results

Research analysis of overflowing phreatic dams showed that special attention is paid to studying the influence of basic geometric parameters of the overflowing phreatic dam downstream slope on quenching level of kinetic energy of the discharged flow.

In this paper, we present the results of model hydraulic studies of overflowing phreatic dams using geosynthetic shells.

Studies of overflowing phreatic dam models with fastening of the downstream slope by geosynthetic shells were carried out at the experimental installation of Environmental and Hydraulic Engineering Department, ACEI, SSTU. The installation scheme is shown in Fig. 2.

Models for slopes fastening by geosynthetic shells were made from colored gypsum elements of a curvilinear transverse profile attached to a plywood sheet. The experiments were carried out for three horizontal equivalent coefficients of the downstream slope m, equal to 1, 2 and 3. The scale of the models was 1:20.

While modeling hydraulic phenomena, the requirements of geometric, kinematic and dynamic similarity were taken into account. The criterion similarity equation for free flow conduit in general form was written as:

$$f\,(Fr;\ Re;\ b_1;\ b_2 \ldots b_n) = 0, \tag{1}$$

where Fr and Re are the Froude and Reynolds hydrodynamic similarity criteria, respectively.

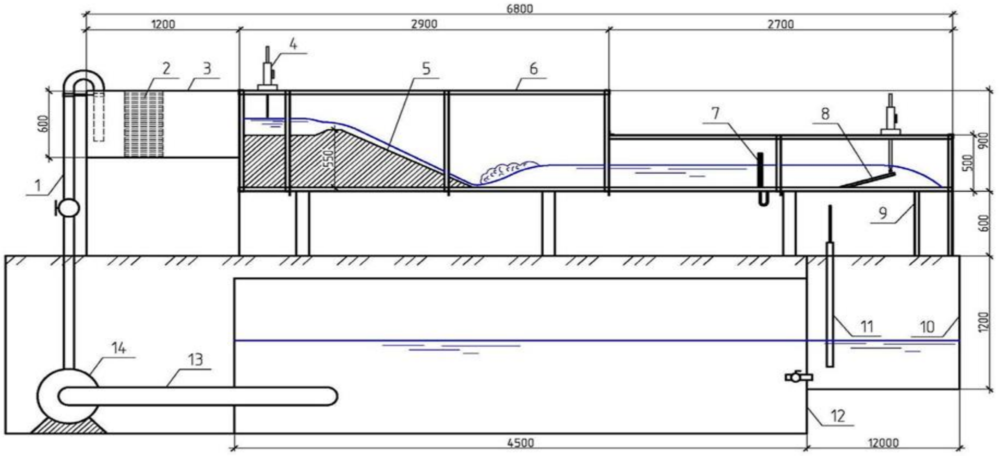


Fig. 2. Experimental installation scheme: 1 - headrace; 2 – quenching grid; 3 - stilling tank; 4 – water gauge; 5 - studied model; 6 - flowing part; 7 - piezometer; 8 - rotary valve; 9 - discharge conduit; 10- gauge tank; 11 - dimensional piezometer; 12 - storage tank; 13 - conduit to the pump; 14 - centrifugal pump. Dimensions are given in mm.

Taking into account the geometric similarity, the condition for hydraulic phenomena modeling in the groove was as follows:

$$Fr = idem \qquad \text{и} \qquad Re > Re_{гр}, \tag{2}$$

where $Re_{гр}$ is the boundary value of the Reynolds number, assumed to be 10^4.

4 Discussion

Step-curvilinear form of overflowing phreatic dam with a downstream slope formed by geosynthetic shells requires the evaluation of its influence on the discharge flow parameters.

Research carried out on models with a step-curvilinear downstream slope showed the following picture of stream flow regime. At low unit discharge on all models the discharged stream repeated the shape of the downstream face, without detaching from curvilinear steps, remaining transparent throughout the depth (Figure 3a), this flow regime can be attributed to the dropping one [5]. As the discharge rate increased the flow picked up speed and from about the second - third of step rise - a jet breakaway and active stream aeration began. Further increase in rate of discharge resulted in shift of active aeration beginning point to the tailrace, the flow becoming transparent throughout the depth, which corresponded to steady-state sliding mode (Figure 3b). When the sliding mode was formed in the step niches of models, a closed eddy roller was formed.

The obtained condition for mode change can be written as

$$\frac{q}{d\sqrt{gd}} > 0{,}31, \tag{3}$$

here d is shell height; q is unite discharge.

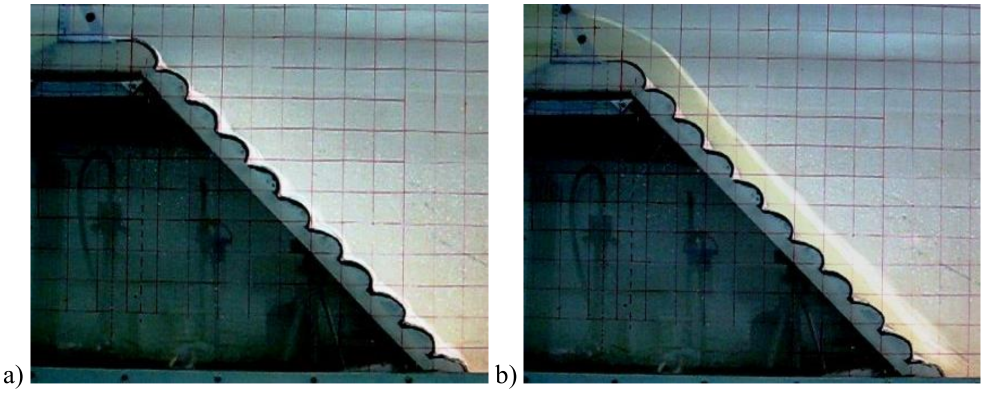


Fig. 3. Flow modes on a model with $m = 1$: a) - dropping; b) - sliding

The estimation of kinetic energy quenching degree of the discharge flow depending on main parameters of the dam downstream slope from geosynthetic shells was carried out by determining the coefficient values of speed φ along the spillway face length of the and in the compressed section behind it.

The speed coefficient is an integral parameter characterizing the total losses of flow head along the drain slope length, i.e. allowing to estimate the quenching degree of excessive kinetic energy within the spillway face and at the spillway bottom.

The experimental coefficient values of velocity in dimensional sections along the spillway face length were determined according to the formula

$$\varphi = \frac{q}{h \cdot \cos\psi \cdot \sqrt{2g(z - h\cos^2\psi)}}, \tag{4}$$

and in the compressed section were determined by the formula

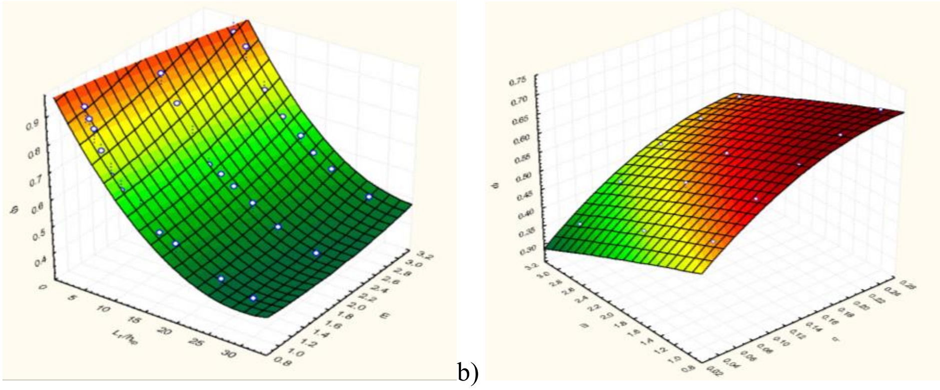
$$\varphi = \frac{q}{h_1 \cdot \sqrt{2g(P + H_0 - h_1)}}, \tag{5}$$

where q is unit discharge; h is flow depth measured in a vertical plane passing through the drain surface bottom in a dimensional section; z is the mark difference of headrace free surface and drain surface bottom in the dimensional section; ψ is the canting angle of drain surface to the horizon; h_1 - compressed flow depth; P is height of spillway rise from the headrace; H_o is head on the spillway crest, taking into account the flow approach speed.

Based on the studies results of the speed change coefficients, the response surfaces of the speed coefficient values along the spillway face were obtained (Figure 4, a) and in the compressed section behind it (Figure 4, b), depending on the downstream slope horizontal equivalent and relative unit discharge.

During the experimental response surface processing (Figure 4a), an equation was obtained to determine the velocity coefficients along the spillway face from geosynthetic shells, horizontal equivalent of the downstream slope of the overflowing phreatic dam being in the range from 1 to 3.

$$\varphi = 0{,}9995 - 0{,}0386 \cdot L_1 / h_{кр} + 0{,}0376 \cdot m - 0{,}0025 \cdot (L_1 / h_{кр}) \cdot m + 0{,}0158 \cdot m^2 \quad . (6)$$



a) b)

Fig. 4. The response surfaces a) - $\varphi = f\left(L_1 / h_{кр}, m\right)$ and b) - $\varphi = f\left(q,\ m\right)$

And when processing the experimental surface (Figure 4, b), the equation for velocity coefficients obtaining in the compressed section is

$$\varphi = 0{,}512 + 1{,}84 \cdot q - 0{,}07 \cdot m - 3{,}58 \cdot q^2 + 0{,}04 \cdot q \cdot m - 0{,}0024 \cdot m^2 \quad . (7)$$

Study results analysis of the main parameters influence of the dam downstream slope from the geosynthetic shells on the kinetic energy quenching degree showed that the change character of kinetic energy quenching efficiency at all the models studied is similar. Thus, with the discharge rates increase and the horizontal equivalent coefficient lowering of the downstream slope, the speed value coefficient increases. The obtained experimental data on the speed coefficients allow us to conclude that on the step-curved downstream slopes the kinetic energy quenching efficiency of the flow within the spillway face can reach 65%.

5 Conclusions

The main conclusions of the research can be formulated as follows.

1. The existing overflowing phreatic dams with the use of stone, concrete, reinforced concrete and metal have typical drawbacks: high material consumption; labor input; expenses. Modern composite materials, such as geosynthetic shells, concrete-filled textile floor-mats and coarse-pored concrete can be used to increase the technological ability and reduce the cost of overflowing phreating dams
2. To substantiate the reliability of new structures of overflowing phreatic dams, including those with composite materials, special model and full-scale studies are required, as well as the development of appropriate design techniques that take into account their design features.
3. Model hydraulic studies of overflowing phreatic dams with the downstream slope formed by geosynthetic shells showed the following: on the downstream face at low unit discharge, a dropping flow mode is observed, as the flow increases, the mode changes onto a sliding one; with discharge rate increase and horizontal equivalent coefficient lowering of the downstream slope, speed coefficient values increase; the quenching efficiency of excessive kinetic energy of the flow within the spillway face from geosynthetic shells can reach 65%. Empirical formulas were obtained for estimating the boundaries of flow mode change and the determination of speed coefficients along the spillway face and in the compressed section.

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