Study of boundary conditions for design of new types of fibre concrete energy dissipators in hydraulic structures

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Abstract. The paper describes experiments aimed at setting parameters for an efficient design of new types and shapes of energy dissipators on chutes of dam spillways. During major rainfall events, large water inflows into the reservoir induce a rise in the reservoir level, and a spillway system must be installed to spill safely the flood waters. Two key challenges during the spillway design are conveyance and energy dissipation. Energy dissipation on dam spillways can be achieved by a range of dissipator designs. One type of spillway is a block ramp. Block ramps are hydraulic structures which are often used in practical applications to assure a correct balance between hydraulic functioning and the environmental impact. One of the main peculiarities of this approach is the capacity to dissipate a larger energy amount than other traditional structures. Thus, significant efforts were spent by the scientific community around the world in order to optimize their energy dissipation efficiency. The use of fibre concrete for the design of reinforced block ramps can improve their resistance significantly. The presented experiments describe the boundary condition for the design of new fibre concrete dissipators based on the measurements performed on reinforced block ramps.

1. Introduction
Reinforced block ramps are structures designed to cross drops in elevation along the longitudinal profile grade of streams. Compared to drop structures, they offer a number of advantages, e.g. better integration in the landscape, preservation of the sediment control regime on the stream and the water habitat migration permeability. Block ramps are therefore often used as fish ladder [1]. The basic requirements for their design are related to sufficient capacity, kinetic energy dissipation and stability of their lining [2]. Block ramps are either designed on streams instead of drop structures or they can also be purpose-designed for spillway tailrace constructions of water reservoirs.

Conveying water across a drop in elevation is always associated with the need to efficiently dissipate the kinetic energy of the water flow on the chute. The boulder chutes provide very good energy dissipation efficiency, which is advantageous in terms of the stability of the reinforcements of the downstream section of the watercourse, which may already be stabilized by another suitable stabilization measures, for example by means of geonets [3]. The first structures designed specifically for water energy dissipation and installed directly on chutes, known as “baffled aprons”, are described in [4, 5, 6]. The study [4], in particular, provided instructions and procedures that have been followed in applications commonly occurring on minor hydraulic structures to-date. The dissipation efficiency of water energy in the torrent control regime was studied e.g. [5, 7]. The spillways of large dams are mostly designed as smooth chutes ended by a ski jump [8, 9, 10]. The reason is easier maintenance...
and reconstruction of simple surfaces. Other options for energy dissipation are a smooth chute ended by a stilling basin or a cascade chute or a smaller stepped chute whose hydraulics are generally discussed, e.g., in [11]. As classic energy dissipation by a water jump in the stilling basin of dams may, in some cases, pose problems, the water flow energy is often dissipated by its aeration, e.g., in a ski jump. Therefore, in structural terms, chutes are relatively demanding structures as they involve dealing with high velocity water flows accompanied by pressure pulsations. This is associated with greater demands for the structural materials used and their higher resistance. For example, fiber concrete which is suitable for constructions with higher requirements can be used advantageously on the one side for small structures (e.g., furniture [12]) and on the other side for huge constructions, e.g., dams. Fiber reinforced concrete meets these increased demands better than plain concrete and, therefore, it has been used in hydraulic engineering for several decades [13, 14]. The main domain where fiber concrete is applied are sections exposed to fast flowing water, or water with sediment transport where abrasion risks arise [15, 16]. It is also used in parts of constructions where the limitation of shrinkage cracks appearance and concrete deformations are desirable [17].

In the chapters below, we will concentrate on the quantification of the efficiency of kinetic energy dissipation and, particularly, on the description of hydrodynamic loading of reinforced block ramp constructions caused by pressure pulsations due to the flowing water.

2. Energy dissipation on block ramps

The quantification of the energy dissipation efficiency on the block ramp can be analyzed using the procedure designed by Pagliara and Chiavacci [18] and presented in the diagram in figure 1. Let us assume a block ramp with the bed slope $S$, which overcomes the difference in elevation $H$ along the length $L$. The critical depth $h_k$ occurs at the ramp entrance in profile No. 0 and, according to the critical flow equation, the total energy of the flowing water above the reference plane $E_0 = H + 1.5h_k$. After profile No. 0 on the chute, a drawdown curve with a super-critical flow regime occurs. Provided the chute is long enough, the uniform flow depth $h_u$ can be reached at the chute end in profile No. 1 and the total energy in profile No. 1 above the reference plane $E_1 = h_u + \alpha v_1^2/(2g)$. Hydraulic losses on the chute are defined by the variable $\Delta E_1 = E_0 - E_1$ and, thus, the relative energy dissipation $\Delta E_r = \Delta E_1/E_0$. Based on the research [18] came to the conclusion that the relative energy dissipation on the chute $\Delta E_r$ primarily depends on the following variables:

$$\Delta E_r = f \left( \frac{h_k}{d_{50}}, \frac{h_k}{H}, S \right)$$

(1)

where $d_{50}$ is the average grain size of the chute material.
Hydraulic losses on a block ramp depend on the chute bed roughness (expressed by the Manning coefficient), which can be calculated using the formula devised by [19]. The respective formula is valid for slopes $S$ ranging from 0.1 to 0.4 and for quarried stone:

$$n = 0.029 \left( d_{50} S \right)^{0.147}$$

where $d_{50}$ is the average grain size of the block ramp in millimetres.

The experiments carried out during our study validated energy dissipation in a block ramp with boulders stabilized in concrete. This application is desirable for large longitudinal bed slopes and in dam spillway tailraces. A characteristic ramp bed cross section is presented in figure 2. The dimensions of boulders are 0.64 to 1.28 m and they are embedded in concrete to half of their depth. Thus, the average boulder size $d_{50} = 0.96$ m, and the mean height of protruding boulders $h_{50} = 0.48$ m. Part of the experiments also dealt with the verification of an alternative with the mean height of protruding boulders $h_{50} = 0.24$ m and a smooth concrete chute. The alternative with the protruding boulder height $h_{50} = 0.24$ m was prepared after the gaps in the preceding alternative of $h_{50} = 0.48$ m had been additionally filled with concrete.

![Figure 2. Block ramp cross section.](image)

Experience gained from many practical applications shows that physical modelling is a useful tool to increase the efficiency of hydraulic research [20]. The experiments were performed on a hydraulic model made in a scale of 1:20. The other block ramp parameters in reality are as follows: the bed slope $S = 0.21$, the chute length $L = 56$ m, the chute height $H = 11.7$ m, the chute width $b = 15$ m. The tested chute will serve as a side channel tailrace of a reservoir and, therefore, a series of discharge rates from $Q_{20}$ to $Q_{10000}$ was verified. These discharges are related to specific discharge rates in the chute in the interval from $q = 1.7$ to 7.1 $m^2.s^{-1}$. The $Q_{10000}$ discharge is the maximum discharge serving, at the same time, to verify the dam safety in floods. Figure 3 below presents a photo of the laboratory hydraulic model in a 1:20 scale.

![Figure 3. Block ramp scale model (1:20): average boulder size $d_{50} = 0.96$ m (left) and smooth chute (right).](image)
The experiments included the assessment of the depth and velocity values at the end of the chute in profile No. 1 as shown in figure 1. The results obtained in this way were compared with the mathematical model, which employed the water level pattern on the chute calculated by the standard section-by-section method in the super-critical flow regime e.g. [21]. This calculation must be performed as it cannot be guaranteed that the very depth of uniform flow will be reached at the end of the chute in profile No. 1 given the respective chute length. Figure 4 displays the comparison of energy dissipation on the chute for the studied roughness alternatives. The plotted charts present the relative energy dissipation on the chute $\Delta E_r$ in relation to the relative height $h_k/H$. The chart also compares the calculated energy dissipation pattern on the chute against the values measured on the scale model.

The chart in figure 4 implies that the relative energy dissipation is the lowest for a smooth surface of the concrete chute and it quickly approaches zero with the growing relative depth $h_k/H$. The growing relative depth $h_k/H$, in this case, corresponds to the situation of a growing critical depth $h_c$ and thus discharge through the chute, or a falling chute height $H$. The falling chute height at the constant slope $S$ corresponds to a shorter chute length. The chart in figure 4 further shows excellent agreement of the relative energy dissipation pattern for a smooth concrete chute and for a chute made with concreted boulders with the protruding height $h_{50} = 0.48$ m. For the protruding boulder depth $h_{50} = 0.24$ m, the energy dissipation is by ca 10% lower than that obtained by the calculation. This circumstance, most likely, results from the fact that the bed roughness $n$ according to the used formula (2) relies on the value $d_{50}$, which was substituted by the depth of the gap between the boulders. For the case of the alternative with boulders half-embedded in concrete, this assumption still well applies according to the measurement, but for the boulders embedded in concrete to three quarters of their height, the actual chute roughness is lower than the calculated one. This results in lower energy dissipation on the chute as it has a smoother surface.

![Energy Dissipation Chart](image)

**Figure 4.** Relative energy dissipation $\Delta E_r$ related to the relative depth $h_k/H$. 
3. Hydrodynamic loading of reinforced block ramps

The primary purpose of using reinforced block ramps is efficient water conveyance across drops in elevation along the longitudinal profile grade of a stream, which is always associated with the need for efficient dissipation of the flowing water kinetic energy. In Chapter 2, the basic approach to the quantification of water energy dissipation on the chute was described in relation to its bed roughness and other parameters. The presented facts imply that the most efficient dissipation can be reached on chutes with macro-roughness elements. The chute roughness can be achieved by the application of man-made dissipators, which are usually made of concrete and possess optimized geometric characteristics. This paper addresses natural block ramps stabilized by mounting individual boulders in concrete. It is evident that dissipation grows with the increasing grains size of the used boulders, but, at the same time, the hydrodynamic loading of the whole chute construction grows, too. This loading is represented mainly by pressure pulsations which can gradually cause the degradation of the chute material reducing its life cycle and serviceability. For this reason, we must try to quantify this oscillating loading and modify the concrete chute construction to resist this load. By integrating pressure pulsations over a defined chute area, the forces acting on the chute as a slab can be successively quantified. The immediate force is defined by the sum of the mean force $F_a$ and the fluctuating force component $F'$. Hence, the pulsating component of the loading force is:

$$F' = \int_A p'dA$$  \hspace{1cm} (3)

where $p'$ is the fluctuating pressure component and $A$ is the defined area for which the resultant compressive force must be specified. The quantification of the resultant compressive force per defined area is important in the stability assessment of slab constructions of hydraulic engineering structures in terms of resistance to lifting due to upward hydrostatic pressure. An example is the quantification of the hydrodynamic loading of the stilling basin bed slab below the weir. In [22] is states that this force loading can be quantified by two procedures. The first approach is direct compressive force measurement (e.g. by means of a transducer) in a part of the construction separated from the rest. In their research, they measured this effect with an experimental device under laboratory conditions. The second approach is based on a statistical assessment of pressure pulsations measured over the loaded area and the quantification of spatial correlations between immediate pulsations. This approach was adopted in their research by e.g. [23, 24].

The pressure pulsation values on the bed are important in terms of the resistance of the concrete parts of the chute. Twelve pressure sensors were installed on the block ramp hydraulic model allowing the monitoring of pressure pulsations for the time $T = 1$ hour with a reading frequency of 1 Hz. The pressure pulsations in individual sensors were standardized using the formula:

$$y = \frac{p - \bar{p}}{\sigma_p}$$ \hspace{1cm} (4)

where $p$ is the immediate pressure value, $\bar{p}$ is the mean pressure and $\sigma_p$ is the standard deviation of pressure. The standardized pressure values show the probability characteristics of the Gaussian probability distribution with a very low deviation of skewness from zero and excess kurtosis from 3. The analysis was processed for all the three chute bed roughness values tested and for a set of values of tested discharges. In this respective case, these were discharges corresponding to $Q_{100}$, $Q_{1000}$ and $Q_{10,000}$, which served for testing the chute behaviour in conveying major flood events. The specific discharges corresponding to the above flood discharges are $q = 2.9; 5.4$ and $7.1$ m$^2$.s$^{-1}$. Figure 5 displays the Q-Q charts (normal probability plot) of standardized pressure pulsations $y$. 
Figure 5. Q-Q charts of standardized pressure pulsations for studied chute bed roughness values and three discharge situations. Standardized pressure pulsations are plotted on the x axis, and the corresponding z-scores of the standard random variables on the y axis.

The charts in figure 5 manifest that pressure pulsations show the Gaussian probability distribution, and the maximum pressure pulsation values can reach 4 times the RMS (root mean square) value defined by the formula:

$$RMS = \sqrt{\frac{1}{T} \int_0^T [(p'(t))^2] dt}$$

(5)

The RMS value depends on the chute bed roughness and the conveyed discharge rate. This relationship was investigated in a case study of a spillway chute. Pressure pulsations on the chute bed were read on the hydraulic model for all the three bed roughness values tested in conveying a series of specific discharges $q$ [m$^2$.s$^{-1}$]. The results of this analysis are documented in an illustrative way in the chart in figure 6. It is evident from the chart that RMS in the case of a smooth bed takes the lowest value increasing only a little with growing discharge rates. In the alternative with the roughest chute bed composed of boulders $d_{50} = 0.96$ m embedded in concrete to half of their depth (gap depth $h_{50} = 0.48$ m), on the contrary, RMS takes the highest value growing significantly with growing discharge rates. In the case of this alternative, the pressure pulsations may amount up to 4 times the RMS value, i.e. ca 1.6 m of the water head (16 kPa), as is documented in figure 7. In the case of low mean pressures or water depths on the chute, total pressure values lower than the atmospheric pressure can be reached on the surface of concrete constructions with some probability. This phenomenon can successively trigger cavitation risks on the concrete surface reducing its life cycle. An efficient preventive measure consists in the reinforcement of concrete parts of chutes with fibre concrete.
4. Conclusion

The presented study brought the following main conclusions: (1) The application of block ramps represents a very beneficial technical solution in conveying water across high drops in elevation along the profile grade of streams. Its benefits include, above all, the preservation of the landscape natural pattern, water habitat migration permeability and the preservation of the sediment control regime. (2) Block ramps provide very good energy dissipation efficiency, which is favourable for the lining stability of the adjacent stream section. (3) Higher energy dissipation is achieved with greater roughness values of the chute. This is accompanied by higher hydrodynamic loading of the chute bed in the form of pressure pulsations. (4) It has been manifested that pressure pulsations have the Gaussian probability distribution and the maximum pressure pulsation values reach up to 4 times the RMS (root mean square) value. (5) The RMS relationship to the chute roughness and the specific discharge has been derived, which may serve for dimensioning chute surfaces made of fibre concrete.

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