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Miroslav SPANO*
Brno University of Technology

PHYSICAL MODELLING OF FLOW OVER STEPPED SPILLWAY OF THE BYSTŘIČKA DAM

Summary. The design parameters of dams (i.e. the spillway design flood) have been recently revaluated in the Czech Republic. It is a reaction to the worldwide trend as well as to extreme flood events occurred in the last ten years.. The Bystřička dam is one of the oldest dams in the Czech Republic. This paper summarizes the results of hydraulic research of the Bystřička dam emergency spillway. Special attention is given to the flow over the stepped part of the spillway.

FIZYCZNE MODELOWANIE POWODZI

Streszczenie. Artykuł reasumuje skutki hydraulicznego badania zapory Bystřička dam, odprowadzającej nadmiar wody w czasie powodzi. Jest to reakcja zarówno na ogólnoświatowy trend, jak i na ekstremalne wydarzenia spowodowane przez powódź, jakie miały miejsce w ostatnich dziesięciu latach. Bystřička dam jest jedną z najstarszych zapór w Czechach. Głównym celem jej działania jest powiększenie bezpieczeństwa podczas powodzi.

1. Introduction – the Bystřička dam

The Bystřička dam was built on the river Bystřička between 1908 and 1912. It is equipped with three bottom outlets and an emergency spillway which is situated outside of the entire dam. The emergency spillway comprises overflow, a spillway channel, and a stepped chute with 21 steps. The spillway is made of quarry stone. The steps are curved in plan and slightly inclined (approx. 3.5°). The ground plan and side section are shown in Fig. 1. The basic parameters of the chute are summarized in table 1.

* Opiekun naukowy: Doc. Ing. Vlastimil Stara, CSc.

Table 1

Basic dimensions of the Bystřička dam stepped chute

I	0.24 (1:4.17)		channel slope
α	13.50	°	angle between horizontal and pseudo bottom lines
w	14.00	m	channel width
h	1.25	m	step height
l	4.90	m	step length
r	0.40	m	radius of step edge rounding

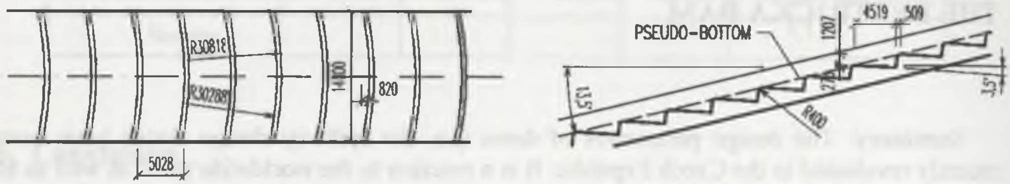

Fig. 1. Ground plan and side section of stepped chute of the Bystřička dam
Rys. 1. Plan pochylni Bystřička dam

The current capacity of the emergency spillway is approx. $Q_{kap} = 101.0\ m^3.s^{-1}$, [1]. The dam was exposed to the highest load from its putting into operation during the flood in 1997. Also, the dam was almost overtopped. According to the actual legislature valid in the Czech republic [2], the Bystřička dam is classified in group A. It means that a safety management of a 10 000-year flood passage with a flow rate of $Q_{10\,000} = 310.50\ m^3.s^{-1}$ is demanded, see [3]. The owner decided to make a reconstruction of the whole dam, see [1]. Within the framework of the reconstruction a modification of the emergency spillway was proposed. Its main aim is the safety passage of a 10 000-year flood. According to these demands the designer (Pöyry Environment, a.s.) proposed a modification of the approaching part, the overflow surface, and the spillway channel, see [3] and/or [4]. With regard to the volume of proposed modifications it was necessary to assess the efficiency of all modifications on a physical model.

2. Model

2.1. Model similarity

Free surface flows (e.g. flow over spillways or chutes) are mainly influenced by gravity forces. Therefore, Froude similarity (Froude number, Fr) is usually used for the modelling of such flows. In the case of stepped chutes the flow is considerably affected by viscosity (Reynolds number, Re) and surface tension (Weber number, We), [5]. Compliance with all similarity conditions for the modelling of aerated flow is only possible when the length scale is $M_L = 1$. Thus, proper choice of the length scale is necessary to get valuable information from the hydraulic model, [5] or [6]. The ratio of flow velocity computed from similarity criteria as a function of length scale when using Froude similarity is shown in Fig. 2. The basic assumption is that there are the same gravity accelerations and the same fluids on the model and prototype with the same physical properties (density, viscosity, surface tension, etc.). It is shown that in comparison with the velocity computed from Re the velocity computed from Fr is less proportional to $M_L^{3/2}$. Similarly, the velocity computed from We is less proportional to M_L compared with the velocity computed from Fr. Thereby, the effect of both viscosity forces (Re) and surface tension forces (We) is intensified. The effect of the gravity force (Fr) is retained. The authors of [7] recommend the choice of the length scale up to $M_L = 25$. The scale effects on smaller models ($M_L > 25$) are causing small efficiency of the model.

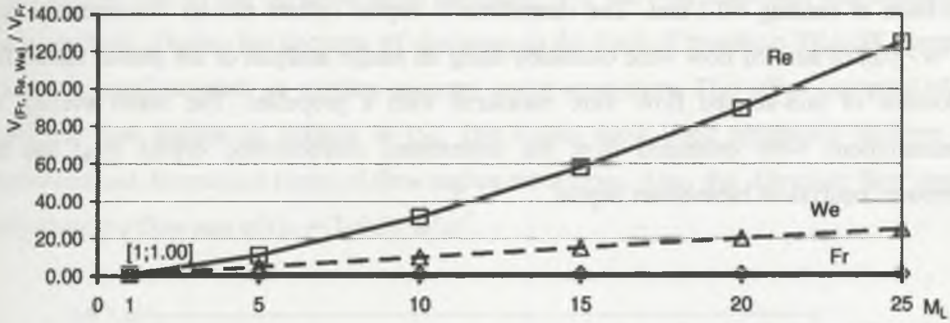

Fig. 2. The ratio
Rys. 2. Stosunek podobieństwa

2.2. Physical model

A physical model of the Bystřička dam emergency spillway was proposed and built in a length scale $M_L = 20$. The model was built in front of the Laboratory of Hydraulic Research of the Water Structures Institute, Faculty of Civil Engineering, Brno University of Technology. The model comprises the approaching part, the overflow, the spillway channel, and the first ten steps of the chute, Fig. 3. The flow on the model is provided by a water supply circuit of the laboratory. The maximum stable discharge of the circuit is approx. 160.0 l. s^{-1}.

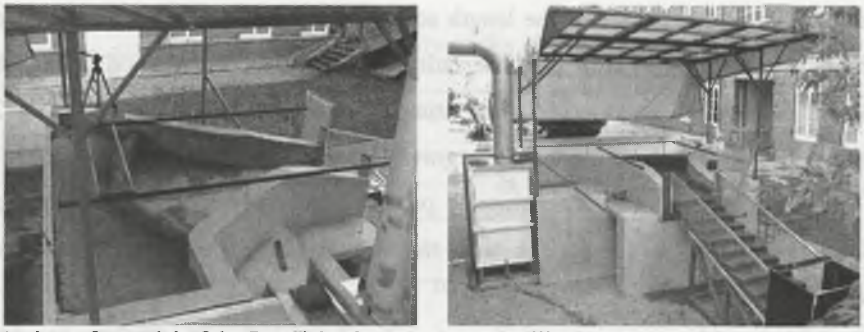

Fig. 3. A view of a model of the Bystřička dam emergency spillway
Rys. 3. Widok Bystřička dam

2.3. Experimental setup

The discharges were controlled with an induction flow-meter. The precision of reading of this equipment is ±1.5 %. The water levels were measured using a point gauge with a precision of reading ±0.1 mm. The characteristic depths (where the air concentration was 90 % - y_{90}) of aerated flow were estimated using an image analysis of the photos taken. The velocities of non-aerated flow were measured with a propeller. The depth average air concentrations were estimated from the determined characteristic depths (y_{90}) and the computed equivalent clear-water depths.

3. Results and discussion

The research of the Bystřička dam emergency spillway was realized in two periods. The first period was focused on assessment of approaching part, the overflow, and the spillway channel. Following text summarizes results of the second period of the research which was focused on assessment of flow over the stepped chute. Results obtained from the experiments were compared with the published results from [5].

All results presented in the following text are converted to prototype.

3.1. Flow regimes

Three regimes of flow on stepped chutes are defined by [5] in dependence on unit discharge and geometry of steps. They include:

- nappe flow regime – NA,

- transition flow regime – TRA,
- skimming flow regime – SK.

Knowledge of the onset of each regime is very important because empirical equations, derived from experiments, are valid only for a specific regime. The limits between flow regimes on the stepped chute are given by the following formula, [5].

$$\frac{d_c}{h} = a - b\frac{h}{l}, \tag{1}$$

where d_c is critical depth [m]; h – step height [m]; l – step length [m]; a, b – regression coefficients. According to [5], the coefficients for transition NA-TRA are a = 0.890, b = 0.400, and for transition TRA-SK a = 1.200, b = 0.325.

The theoretical limits of transitions between flow regimes and the limits seen on the model of the Bystřička dam are shown in fig. 4. The limits of flow regimes were assessed visually. The determination of the transition NA-TRA was not easy. The rounded shape of the step edges caused that no jets occurred along the chute. The TRA-SK transition was determined more precisely. During the decrease of discharge to the limit of transition TRA-SK (approx. 70 $m^3.s^{-1}$), small unstable air cavities occurred under some steps. This effect is typical of the transition flow regime as defined in [5]. The results show good agreement between the theoretical and determined limits of flow regime transitions. Also, the skimming flow regime will occur at a flow rate of $Q_N = 310.50\ m^3.s^{-1}$.

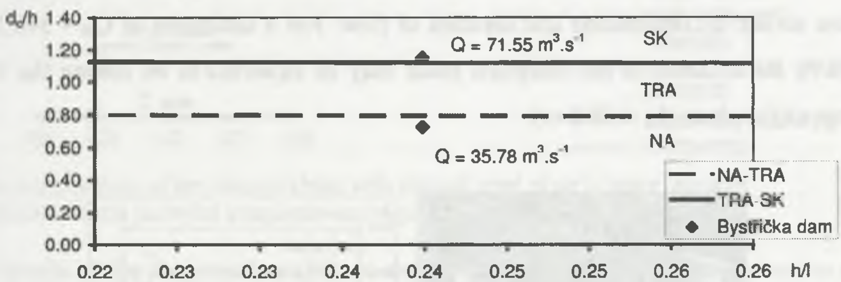

Fig. 4. Limits between flow regimes on stepped chutes according to [5] and limits seen on the model of the Bystřička dam

Rys. 4. Różnice pomiędzy ograniczeniami wg [5] a ograniczeniami omawianego modelu

3.2. Inception point

The location of the point where the aeration starts (the so-called inception point) was the main question of the second period of the research. The results of the measurements were compared with the theoretical location of the inception point. The theoretical location was computed according to the formula from [5]. The formula is valid for the skimming flow regime (SK):

$$L_I = a \cdot F^{*b} \tag{2}$$

$$F^* = \frac{q_w}{\sqrt{g \cdot \sin\alpha \cdot k_s^3}}, \tag{3}$$

where L_I is distance of the start of growth of the boundary layer to the inception point of air entrainment (in this case it was considered that the boundary layer grows from the brink of the first step of the chute) [m]; q_w – unit discharge [$m^2.s^{-1}$]; $g = 9.81\ m.s^{-2}$ – gravity acceleration [$m.s^{-2}$]; α – channel slope [rad] ; k_s – channel roughness [m]; F^* - Froude number defined in terms of the roughness height; a, b – regression coefficients. In the case of the Bystřička dam the coefficients are according to [5] equal to a = 11.489 and b = 0.713.

The effect of the discharge on the location of the inception point and a comparison of the theoretical and experimental location of the inception point are shown in Fig. 5.

The results of the research have shown that the observed location of the inception point is different from the theoretical location computed in [5]. The aeration on the Bystřička dam chute began earlier than predicted by the theoretical computation. Many reasons can cause this difference, for example the shape of steps (edge rounding, small inclination of steps), wrong consideration about the location of the start of growth of the boundary layer, scale effects, etc. One of the main reasons may be a relatively small height of steps, [5]. For smaller discharges, the flow is “broken” by the edges of the downstream steps. The turbulences grow and cause earlier decomposition and aeration of flow. For a discharge of $Q_N = 310.50\ m^3.s^{-1}$ ($F^* = 10.9$), the location of the inception point may be expected to be among the 10th and 11th steps of the chute ($L_I = 58.6$ m).

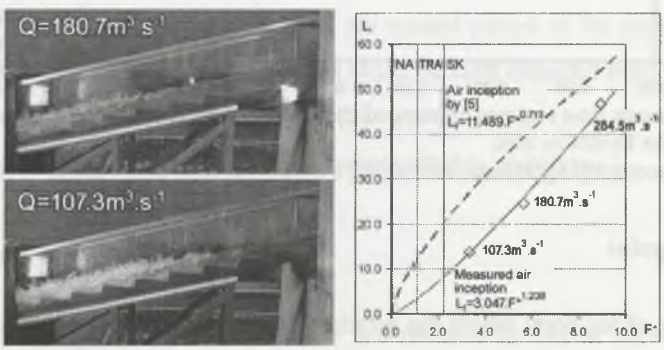

Fig. 5. The effect of the discharge on the location of the inception point and a comparison of the Estimation of air amount

Rys. 5. Skutki obciążeń oraz porównanie teoretycznych i doświadczalnych punktów

Air concentration belongs to important characteristics of air-water flow. It is defined as the ratio of air volume and air-water mixture volume. The aeration produces flow bulking and therefore requires higher sidewalls of the chute. The relation between air-water mixture depth and depth averaged air concentration is given by formula (4), [5].

$$\overline{C} = 1 - \frac{d}{y_{90}}, \tag{4}$$

where $\overline{C}$ is depth average air concentration, y_{90} – characteristic depth where air concentration is 90 % [m], d – equivalent clear-water depth [m].

A depth averaged air concentration on the Bystřička dam chute was estimated at the brink of each step according to formula (4). The depths y_{90} were estimated using an image analysis of flow photos. The equivalent clear-water depth was computed with a 1D mathematical model of flow in a smooth channel with high roughness. The model was calibrated at higher discharges when no air entrainment was observed. The results of the experiment for a discharge rate of Q = 107.3 $m^3.s^{-1}$ are shown in Fig. 6.

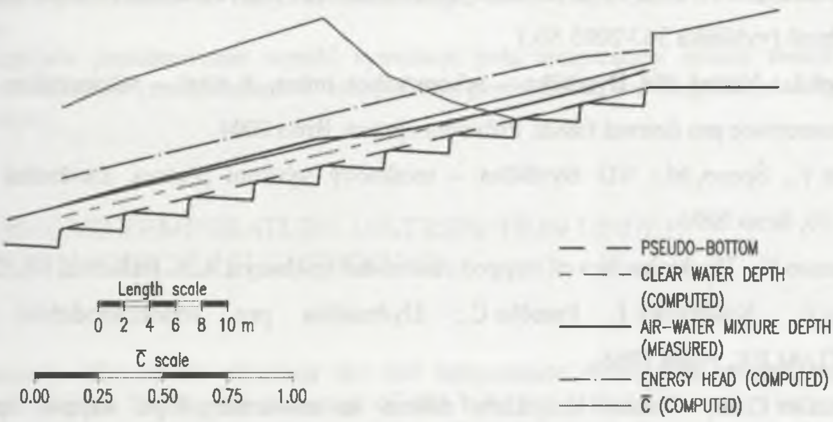

Fig. 6. An axial section of the stepped chute with plotted level of air – water mixture
Rys. 6. Osiowa sekcja pochylni z zaplanowanym poziomem powietrze – woda

The results of the analyses have shown that the depth averaged air concentration reached values from 0.0 to 0.57, which causes an increase of depth by 133%. The aeration increases from the inception point but becomes constant after a few steps. A detailed study which was performed for more discharges shows that the stable value of depth averaged air concentration is approximately up to 0.60.

4. Conclusions

Flow over stepped chutes is very complex. Therefore, its modelling represents a hard problem. Special attention has to be paid to the choice of the length scale when modelling this effect. High demands are also set on the experimental setup (e.g., a probe for the measurement of air concentration, etc.).

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