A Comparative Study of Self-aerated Stepped Spillway and Smooth Invert Chute Flow: The effect of Step-induced Macro-roughness

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Abstract

Due to the rapid development of roller-compacted concrete technique in dam construction research interest in stepped spillway hydraulics increased in recent years.

Because of the strong turbulence enhanced by the step-induced macro-roughness the flow velocity is lower than on comparable smooth spillways. By consequence, a higher flow resistance and hence, a higher energy dissipation must be noted as a main characteristic.

Earlier investigations indicate that the energy dissipation potential is only slightly influenced by a change of slope on embankment stepped spillways with moderate slopes between 18.4° and 26.6° [2].

In order to quantify the general effect of the macro-roughness a comparative study of self-aerated flow on stepped spillways and smooth invert chutes, respectively, with a slope of 26.6° has been carried out.

Keywords: Spillways, Self-aeration, Energy dissipation

1. Introduction

Spillways are open or closed channels integrated in dams used for conveyance of water from upstream to downstream during flood events. In order to protect the dams spillways need to have a large capacity which is achieved by high slopes and hence, by large flow velocities. Due to growing of the turbulent boundary layer at the crest a critical point can be found (assumed that the structure is high enough) where self-aeration of the water flow occurs. This aeration helps to prevent damages caused by cavitation. However, due to the high velocities (i. e. > 20 m/s) additional devices (e. g. spilling basins) are required in order to dissipate the residual energy head at the toe.

In recent years the Roller-Compacted Concrete technique in dam constructions has been rapidly developed. Due to the pyramidal shape of this type of dam stepped spillways are easy to integrate and become more and more popular. These cascades are characterized by an earlier self-aeration and a higher energy dissipation caused by the strong turbulence. The latter is caused by the macro-roughness which is enhanced by the steps. This paper aims to compare both types of spillways qualitatively by physical model investigations in order to describe the effect of a presence of steps and the step heights.

2. Methodology

2.1. Model setup

Experiments are conducted on a physical model scaled 1:10 with a chute width b of 30 cm and a total drop height H_{dam} of 2.34 m (Fig. 1). Water is pumped into a system of two open head tanks. Small tubes are installed in the approaching channel in order to distribute and calm down the flow before being conveyed. Two pumps generate a total discharge Q up to 45 l/s controlled by a flap valve. The discharge is checked with an IDM system and verified with an ultrasonic sensor installed in the approaching channel in combination with an appropriate calibrated rating curve.

Figure 1. Physical model with H = 2.34 m, φ = 26.6°, step height s = 3 cm and specific discharge q = 0.09 m²/s (note the clear water region near the spillway crest)

Self-aerated flow parameters on stepped spillways are investigated on a physical model with a slope of φ = 26.6° and step heights s of 3 cm and 6 cm, respectively. Observed specific discharges q vary from 0.07 to 0.11 m²/s. With given hydraulic and geometric boundary conditions skimming flow regime sets in on all stepped spillway model tests. In this flow regime water flows down as a coherent stream above the imaginary pseudo-bottom formed by the step edges (Fig. 2).

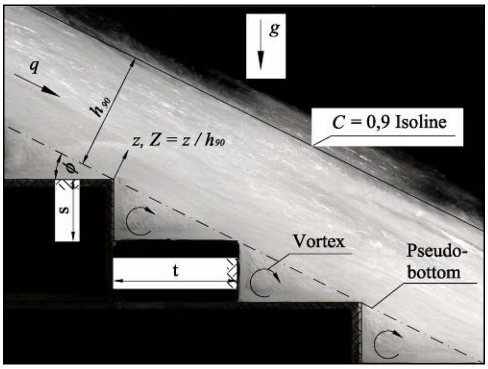
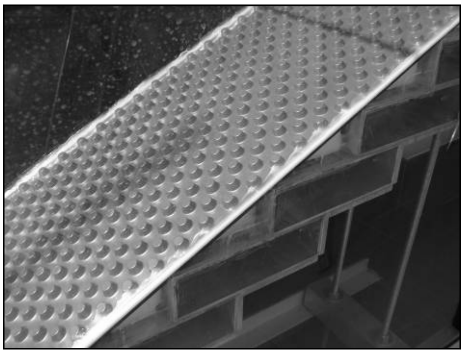


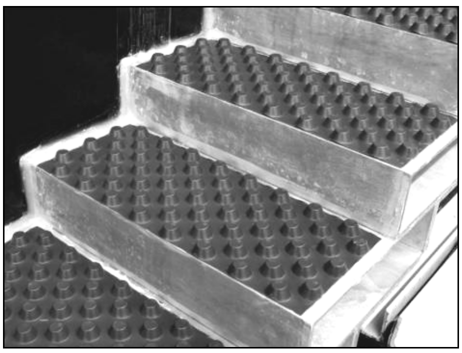
Figure 2. Sketch of skimming flow on an embankment stepped spillway compared to physical model test (φ = 26.6°, s = 6 cm, q = 0.11 m²/s)

Within the step niches vortices are generated and maintained by the shear stress between the main flow and the cavity flow. Here a large part of the total energy dissipation is taking place.

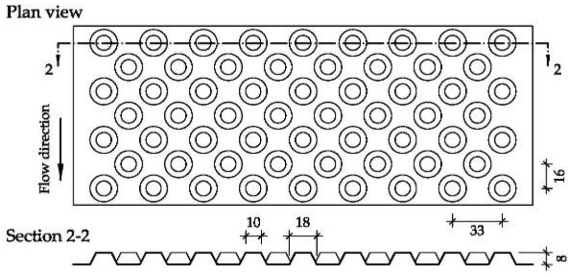
Observing a stepped spillway overflow from outside the skimming flow regime is not distinguishable from flow on a smooth spillway.



a) Photo of smooth invert chute



b) Photo of stepped chute



c) Sketch (all dimensions in mm)

Figure 3. Artificial micro-roughness

The self-aerated flow on a smooth spillway with the same slope is investigated by attaching a smooth invert to the above described model setup. In order to enhance the self-aeration process which primarily depends on the surface roughness on smooth spillways the chute's PVC bottom is equipped with additional artificial micro-roughness elements (Fig. 3a).

Obviously the scaling to prototypes becomes unfeasible. However, the general flow characteristics are unaffected by this approach.

In order to quantify the effect of this artificial roughness in comparison to the step-induced macro-roughness on stepped spillways a comparative study of a cascade (s = 6 cm) is conducted with a superposed roughness (Fig. 3b). Since it was found that the characteristics of the results are nearly unaffected by the discharge, the presented result plots (Fig. 6-11) are limited to q = 0.11 m²/s.

2.1. Measuring of air-water flow properties

Air-water flow properties are investigated by use of an intrusive double tip conductivity probe (Fig. 4, developed by IWW, RWTH Aachen). Each tip consisting of an electrode with a diameter of 130 μm samples a high or low voltage in dependence of the surrounding medium (water or air). The sampling rate is 25 kHz and the sampling duration is 25 s for all experiments.

Figure 4. Double-tip conductivity probe for measuring of air content and flow velocities (note: 2 electrodes with a distance in flow direction of 5.1 mm)

By cross-correlation of both signals the resulting time lag, which gives the maximum correlation factor, may be assumed as the traveling time of air bubbles between these two tips. With knowledge of the tip distance in flow direction - which is 5.1 mm - the flow velocity of the air-water mixture may be calculated.

Besides the flow velocity, void fraction and bubble sizes can be determined by a simple processing of the sampled raw signals.

Exact positioning of the probe is guaranteed by use of a two-dimensional linear guide system which is operated by a CNC controller (isel).

3. Inception point of self-aeration

A characteristic point for spillway flows is the inception point of self-aeration or so-called critical point [6]. In the approaching channel a growing turbulent boundary layer can be found. When this boundary layer reaches the water surface the self-aeration sets in (Fig. 5).

Since air entrainment is not a sudden but a gradually developing process, an accurate definition of the critical point is difficult. Most of earlier researches on stepped spillways result in a mean air concentration at the point of inception of about 20 % (cf. [1] and [4]). For better comparability this value - which could be verified in the experiments - has been adopted in the following analyses.

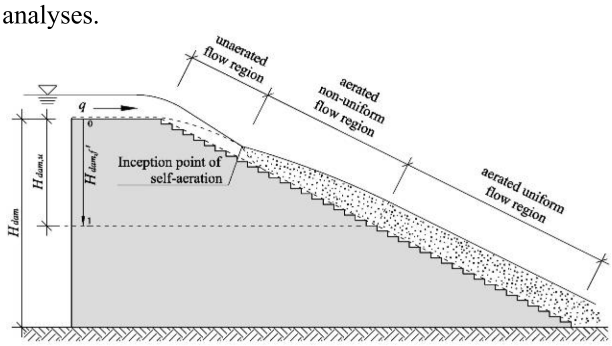


Figure 5. Flow regions in skimming flow regime on stepped spillways (identical to smooth spillway flows)

Tab. 1 summarizes the dam heights $H_{dam,i}$ required for the attainment of aerated flow for all experiments as well as the flow depths h_i at the critical point. It has to be noted that smooth invert chutes generally lead to a longer unaerated flow region than stepped spillways because of the lower turbulence. The fact that $H_{dam,i}$ is decreasing from s = 3 cm to s = 0 cm is caused by the artificial, unscalable roughness used in the experiments. According to [6] the surface roughness is the controlling parameter in regard to self-aeration (for a constant discharge and slope).

In consideration of the Bernoulli equation the decreasing flow depths h_i at the critical point for smooth invert chutes indicate a higher acceleration near the spillway crest. In the presence of steps the step height itself is only slightly influencing the flow depth h_i at the inception point of self-aeration.

Table 1. Critical points (φ = 26.6°, AR: artificial roughness)

q [m²/s]	s [cm]	$H_{dam,i}$ [m]	h_i [m]
0.07	0 (AR)	0.360	0.025
	3	0.420	0.028
	6	0.300	0.029
	6 (AR)	0.300	0.031
0.09	0 (AR)	0.480	0.030
	3	0.540	0.032
	6	0.390	0.033
	6 (AR)	0.390	0.036
0.11	0 (AR)	0.601	0.033
	3	0.691	0.038
	6	0.450	0.038
	6 (AR)	0.510	0.039

4. Attainment of uniform flow

It is assumed that uniform sets in when the flow depths, the mean flow velocity and the mean air content remain constant in flow direction. The experiments prove that the dam height $H_{dam,u}$ which is required for the onset of uniform flow, is mainly a function of the discharge for a given spillway slope and nearly unaffected by the step height. The difference in $H_{dam,u}$ for a stepped spillway with s = 6 cm and a smooth invert chutes (with artificial roughness) has been found to be in the range of only 10%. For φ = 26.6° the onset of uniform flow may be estimated by:

$$H_{dam,u} \approx 14 h_c \tag{1}$$

5. Flow depths

Due to bubbles and droplets the flow depth cannot be specified directly in the aerated flow region. However, knowledge of the flow depths is essential for design purposes. For instance the depth of the air-water mixture defines the required height of training walls.

Measurements prove that only a negligible part of the total discharge is taking place above the characteristic depth h_{90}, i.e. the flow depth where the air concentration is 90 %. Thus, this characteristic flow depth is often assumed as the air-water mixture depth.

Moreover, the clear water depth $h_w = h_{90}\left(1-\overline{C}\right)$, with $\overline{C}$ the mean air concentration at a particular location, is the decisive factor regarding determination of friction factors.

Fig. 6 illustrates the development of the air-water mixture depth h_{90} in dependence of the critical water depth h_c and the location on the structure. $H'_{dam,f} = H_{dam,f} / H_{dam,u}$ is a dimensionless drop height in non-uniform flow region relating the absolute drop height $H_{dam,f}$ to the drop height $H_{dam,u}$ required to attain uniform flow. Hence, it can take values from 0 to 1 (see Fig. 5). Obviously, the aerated flow depth is increasing with higher drop height for all configurations. This is due to the so-called "Flow Bulking" generated by increasing aeration. Furthermore, h_{90} is significantly increased by the macro-roughness on stepped spillways. In practice, higher chute walls will be required for stepped spillways.

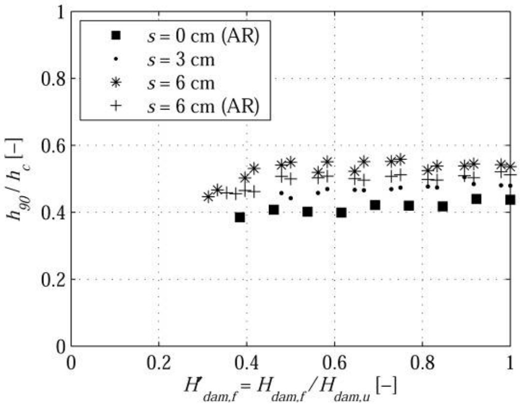


Figure 6. Development of air-water mixture depth h_{90} in non-uniform flow region (φ = 26.6°, q = 0.11 m²/s, AR: artificial roughness)

In contrary, the clean water depth h_w is slightly decreasing within the non-uniform flow region. This decrease is caused by acceleration of the flow. A significant difference of about 15 % to 20 % in clear water depth between the stepped spillway models and the smooth invert chute model must be noted (although the flow resistance is even strongly enhanced by use of the artificial roughness here). As it will be shown later the reduced clear water depth corresponds to higher flow velocities and hence, to a decreased flow resistance.

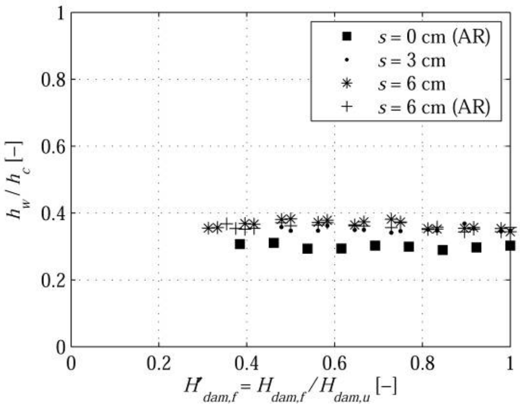


Figure 7. Development of clear water depth h_w in non-uniform flow region (φ = 26.6°, q = 0.11 m²/s, AR: artificial roughness)

6. Air concentration

Since h_w and h_{90} decrease in the same order the mean air concentration $\overline{C} = 1 - h_w / h_{90}$ is nearly unaffected by the macro-roughness (Fig. 8). For example, the mean air content is approximately $0.30 \le \overline{C} \le 0.35$ in uniform flow region for all configurations.

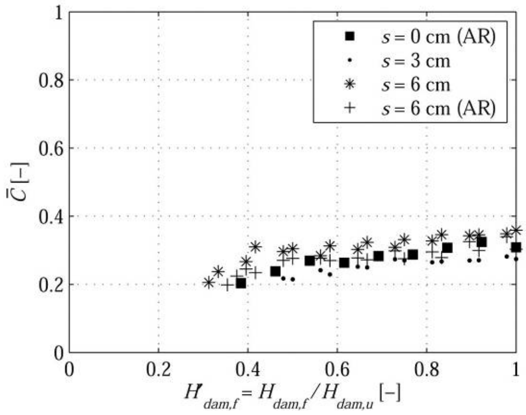


Figure 8. Development of mean air content $\overline{C}$ in non-uniform flow region (φ = 26.6°, q = 0.11 m²/s, AR: artificial roughness)

Air concentration models based on theoretical considerations are presented by [3] and [7]. As a result the air concentration distribution is a function of the mean air content only. Typical air concentration profiles, measured in uniform flow region, are illustrated in Fig. 9. The air concentration distributions on smooth invert chutes are similar to those on stepped spillways.

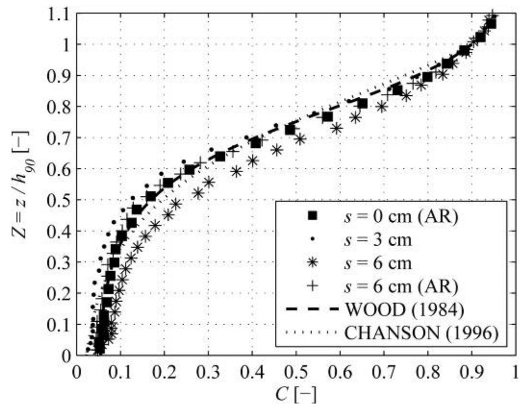


Figure 9. Air concentration distributions in uniform flow region (φ = 26.6°, q = 0.11 m²/s, AR: artificial roughness, data at step edges for stepped spillway models) in comparison to theoretical models by [3] and [7] with $\overline{C} = 0.30$

For spillway design purposes the bottom air concentration is of particular importance. A high air content near the bottom helps to prevent damages from cavitation at the spillway bed which is caused by the high-speed flow and the corresponding low pressures. This cavitation may lead to severe structure failures. Fig. 9 illustrates that this parameter is nearly unaffected by the presence of step-induced macro-roughness. However, it has to be noted that the bottom air concentration may be significantly enhanced by the artificial surface roughness for the smooth invert chute. The transferability of this result needs to be proved by further investigations.

7. Flow velocities

As a conclusion of the reduced flow depths on smooth invert chutes (Fig. 7) a higher flow velocity was assumed. Fig. 10 presents the velocity distributions for all configurations in uniform flow region in dependence of the critical water depth h_c and the critical flow velocity u_c.

Generally the velocity profiles follow a power function for all configurations. However, results in Fig. 10 prove that velocities are constant above the dimensionless depth $z / h_c = 0.30$.

Furthermore, it can be found that the velocity of the air-water mixture increases with decreasing step height. Moreover, Fig. 9 shows that the flow velocity in uniform flow is about 4 times the velocity at the spillway crest (which theoretically can be assumed to be equal u_c).

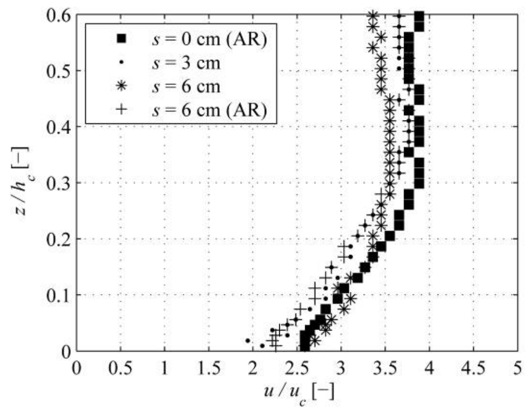


Figure 10. Velocity distributions in uniform flow region ($\varphi = 26.6°$, $q = 0.11$ m²/s, AR: artificial roughness, data at step edges for stepped spillway models)

8. Flow resistance and energy dissipation

Even on stepped spillways, where the flow resistance is generated by a series of spot losses enhanced by the steps, Darcy's approach may be applied. For determination of the friction factor f the clear water depth must then be taken into account. Thus, assuming the hydraulic diameter to be $D \approx 4h_w$ the flow resistance in uniform flow region (where the energy gradient equals the chute slope φ) becomes:

$$f = 8g \sin\varphi \frac{h_w^3}{q^2} \qquad (2)$$

Obviously, even a small change of clear water depth yields to a significant effect on the friction factor and hence on the energy dissipation. The experiments show that the effect of the macro-roughness on the friction factor in case of stepped spillways is negligible. Here the flow resistance is $f = 0.10$ for all configurations [2]. In contrary, in case of the smooth invert chute the Darcy coefficient becomes $f = 0.06$. Both values are determined by use of a correction method eliminating the influence of the hydraulically smooth sidewalls in the physical model. Moreover a shape correction is applied taking into account the given rectangular cross-section differing from the circular shape supposed in the basic theory. The correction methods are exemplary described by [5].

It has to be noted that the flow resistance in case of the smooth invert chute is significantly influenced by the artificial roughness which has been installed in order to force the self-aeration on the very smooth PVC-bottom used in the laboratory. A study of the nearly unaerated flow obtained on the smooth invert chute without the artificial roughness even resulted in a friction factor of only $f = 0.02$ which is only 20 % of the flow resistance of stepped spillways with the same slope.

9. Summary & Conclusions

A qualitative comparison of stepped spillways in skimming flow regime and smooth invert chutes has been carried out.

The results prove that significant differences in regard to external flow features exist. Here, the step-induced macro-roughness leads to an earlier self-aeration and to higher flow depths. Thus, the cavitation risk near the spillway crest is reduced on stepped spillways on the one hand and energy dissipation is increased on the other hand.

The internal flow features like air concentration and velocity distributions are nearly unaffected by the step-induced macro-roughness.

10. References

[1] Boes, R. M. and Hager, W. H. (2003): "*Two-phase flow characteristics of stepped spillways*." J. Hydr. Eng. 129 (9), 661-670.

[2] Bung, D. B. (2009): "*Zur selbstbelüfteten Gerinneströmung auf Kaskaden mit gemäßigter Neigung*." Doctoral dissertation, Bergische Universität Wuppertal, Shaker Verlag, Aachen.

[3] Chanson, H. (1996): "*Air bubble entrainment in free-surface turbulent flows*." Academic Press, San Diego.

[4] Matos, J., Pinheiro, A. N., de Carvalho Quintela, A. and Frizell, K. H. (2001): "*On the role of stepped overlays to increase spillway capacity of embankment dams*." ICOLD European Symposium (NNCOLD), Geiranger, Norway.

[5] Schröder, R. C. M. (1990): "*Bestimmung von Rauheiten*." In: Hydraulische Methoden zur Erfassung von Rauheiten (DVWK Schriften 92).

[6] Wood, I. R., Ackers, P. and Loveless, J. (1983): "*General method for critical point on spillways*." J. Hydr. Eng. 109 (2), 308-312.

[7] Wood, I. R. (1984): "*Air entrainment in high-speed flows*." Symposium on scale effects in modeling hydraulic structures. Stuttgart, Germany.