Energy dissipation and air entrainment on stepped spillways with non-uniform cavity sizes

S. Felder[1] and H. Chanson[1]
[1]School of Civil Engineering
The University of Queensland
Brisbane QLD 4072
AUSTRALIA
E-mail: s.felder@uq.edu.au

Abstract: *An experimental study was conducted on a large size stepped spillway model with a moderate slope (26.6º) for a range of discharges between 0.020 and 0.237 m^3/s. In some experiments, the stepped chute was equipped with uniform steps of 5 and 10 cm heights respectively. In addition several non-uniform configurations with combinations of 5 and 10 cm high steps were investigated. For each configuration, the air-water flow properties were measured for several discharges. The study yielded some challenging outcomes in terms of energy dissipation and aeration on stepped spillways with non-uniform cavity sizes. A comparative analysis with the stepped spillways with uniform step heights showed that the energy dissipation rate, the residual head, the flow resistance and the mean air concentration were close for all geometries. This might be used for the design of prototype spillways with non-uniform step heights, but the flow pattern of the non-uniform step configurations showed some instabilities. A stepped spillway design with uniform step heights is the preferable design option.*

Keywords: *Stepped spillway, non-uniform step height, energy dissipation, residual energy, air-water flows, design guidelines*

1. INTRODUCTION

Stepped spillways are a common design for flood release facilities. The steps act as rough elements that cause large flow resistance and increase significantly the energy dissipation rate. The design is cheaper because the size of the downstream energy dissipation structure can be reduced and the stepped geometry might be a feature of the construction technique (Chanson, 2001b). A further key characteristic is the strong air entrainment which is caused by large turbulence levels next to the free surface at and throughout downstream of the inception point of free surface aeration. Significant amounts of air exist in the air-water flow column which reduces the risk of cavitation. Air-water flows on stepped spillways are complex and many experimental studies have been conducted for typical stepped spillway designs with flat horizontal steps and various spillway slopes (e.g. Boes, 2000; Matos, 2000; Toombes, 2002; Gonzalez, 2005; Chanson & Carosi, 2007; Felder & Chanson, 2009b).

Figure 1 Stepped spillway of the Tillot dam in France with non-uniform step height

However some prototype spillways are equipped with non-uniform step heights: e.g. Tillot dam (1835) in France (Figure 1), Malmsburry (1870) and Upper Coliban (1903) stepped spillways in Australia (Chanson, 2001a). The Australian spillways were designed with drops of 2 to 4 m followed by smaller steps of 0.305 m. The long operation of the spillways indicate that the design is sound although a nappe flow exists for the large drops and a skimming flow regime for the small step heights for the design flow (Chanson, 2002). Some flow instabilities and shock waves might occur for the non-uniform step heights as reported by Toombes & Chanson (2008) in the nappe flow regime and by Thorwarth & Köngeter (2006) for pooled stepped spillways. The only experimental test of non-uniform step heights have been conducted by Stephenson (1988) on a model with a slope of 45º. In a test with occasionally large drops, he observed an increase of energy dissipation of 10%. In the present study, the effects of non-uniform step heights on the flow pattern, the energy dissipation rate and the aeration performance were tested systematically for a wide range of discharges.

2. EXPERIMENTAL SETUP

In the present study, the experiments were conducted on a large size stepped spillway model with a channel slope of θ = 26.6º. The same channel has been successfully used in previous experimental studies with different slopes and details about the experimental facility can be found in Toombes (2002), Chanson & Carosi (2007) and Gonzalez & Chanson (2007a). The experiments were conducted with uniform step heights h of 5 and 10 cm respectively. In addition a number of non-uniform configurations of combinations of 5 and 10 cm step height were investigated. The three non-uniform configurations are listed in Table 1 and the Reynolds numbers and the discharges are added in dimensional terms per unit width q_w and dimensionless terms as d_c/h, where d_c is the critical flow depth. The non-uniform configurations are sketched in Figure 2.

Table 1 Summary of experimental configurations for non-uniform step heights

Configuration	Steps	q_w [m^2/s]	d_c/h	Re	Comment
A	10 steps (h = 5 cm) 5 steps (h = 10 cm)	0.057 - 0.237	0.7 - 1.85	2.3 10^5 - 9.4 10^5	Calculation of d_c/h with h = 10 cm
B	9 steps (h = 10 cm) 2 steps (h = 5 cm)	0.057 - 0.237	0.7 - 1.85	2.3 10^5 - 9.4 10^5	Calculation of d_c/h with h = 10 cm
C	18 steps (h = 5 cm) 1 steps (h = 10 cm)	0.021 - 0.21	0.7 - 3.4	8.2 10^4 - 8.3 10^5	Calculation of d_c/h with h = 5 cm
uniform (h = 10 cm)	10 steps (h = 10 cm)	0.057 - 0.237	0.7 - 1.85	2.3 10^5 - 9.4 10^5	Calculation of d_c/h with h = 10 cm
uniform (h = 5 cm)	20 steps (h = 5 cm)	0.021 - 0.218	0.7 - 3.5	8.2 10^4 - 8.7 10^5	Calculation of d_c/h with h = 5 cm

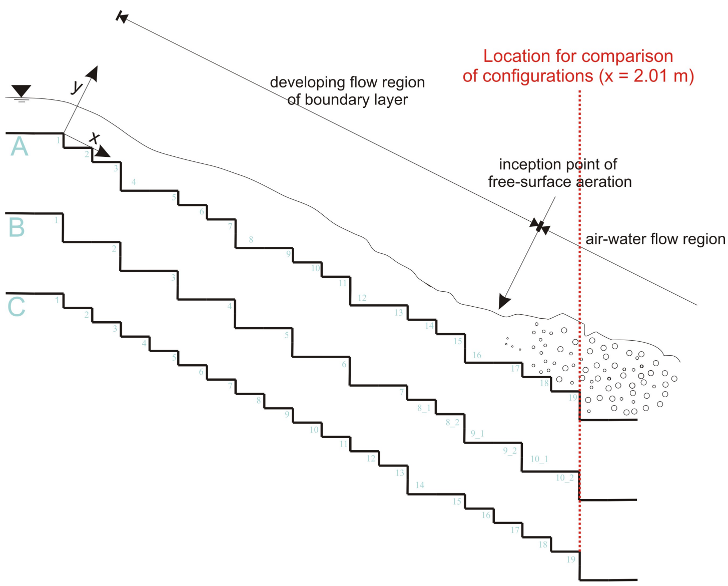

Figure 2 Sketch of non-uniform model configurations: from top to bottom configuration A, B, C

For all channel configurations, the air-water flow properties were measured at the downstream end of the spillway with a double-tip conductivity probe with probe tip diameters of 0.25 mm. The probe tips had a separation of 7.2 mm in the streamline direction and the probe was positioned with a digimatic scale in the direction perpendicular to the pseudo bottom formed by the step edges. All measurements were conducted for 45 seconds at 20 kHz per sensor.

3. AIR-WATER FLOW PATTERN

For all stepped spillway configurations with uniform and non-uniform step heights, the flow pattern was observed for the full set of discharges and for all three flow regimes. The observations included the locations of the inception point of air entrainment and the changes in flow regimes from nappe (NA) flows to transition (TRA) flows and from TRA to skimming (SK) flows as listed in Table 2. For configuration C, the observation of the flow regime change of TRA - SK is not definite. At the upstream end of the chute, the step heights of 5 cm resulted in identical changes of flow regimes as observed for the stepped channel with uniform step heights of 5 cm. But the large drop of 10 cm at the lower end of the chute led to different flow patterns downstream of the drop, i.e. a transition flow regime existed still for d_c/h < 1.73 before the flow regime changed to a skimming flow regime. All configurations with non-uniform step heights showed some flow instabilities.

Table 2 Summary of flow regime changes for different channel configurations (θ = 26.6º)

Configuration	NA - TRA	TRA - SK	Comment
A	d_c/h = 0.53	d_c/h = 1.0	Calculation of d_c/h with h = 10 cm
B	d_c/h = 0.6	d_c/h = 1.0	Calculation of d_c/h with h = 10 cm
C	d_c/h = 0.53	d_c/h = 1.73 (1.07)	Calculation of d_c/h with h = 5 cm
h = 10 cm (uniform height)	d_c/h = 0.6	d_c/h = 0.93	Calculation of d_c/h with h = 10 cm
h = 5 cm (uniform height)	d_c/h = 0.53	d_c/h = 1.07	Calculation of d_c/h with h = 5 cm

For the largest flow rates, a skimming flow regime existed. At the upstream end of the stepped chute the water was non-aerated and looked glassy. At the inception point of free surface aeration, significant air entrainment occurred and a turbulent two-phase flow existed downstream. Several mechanisms led to significant energy dissipation including cavity recirculation and large turbulence levels in the bulk of the flow. Figure 3 shows the flow pattern in skimming flows for configuration A.

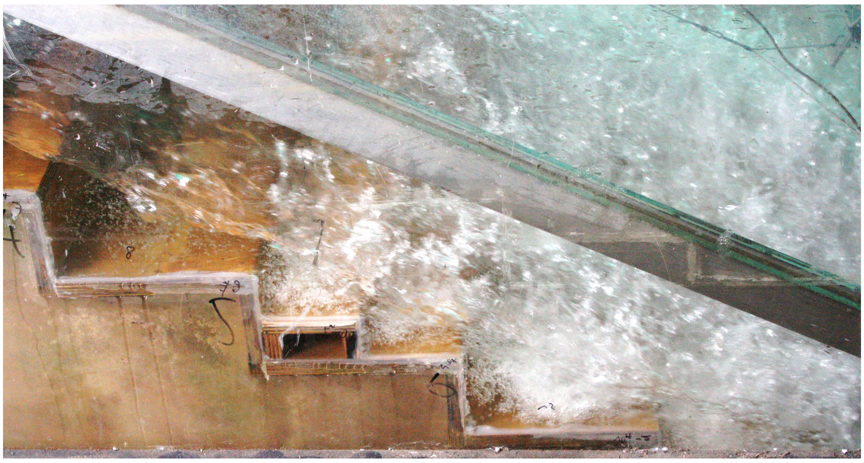

Figure 3 Skimming flows, inception point of free surface aeration and cavity recirculation for configuration A; d_c/h = 1.27; Re = 5.4 10^5; q_w = 0.137 m^2/s; h = 0.1 & 0.05 m; θ = 26.6º

4. COMPARISON OF AIR-WATER FLOW PROPERTIES

For all configurations with uniform and non-uniform step heights, the energy dissipation, the residual head and the mean air concentration C_{mean} were calculated in both transition and skimming flow regimes. The results were compared in terms of the air-water flow properties at the downstream end of the spillway, i.e. at an identical longitudinal distance measured from the weir crest x = 2.01 m (Figure 2). Furthermore the flow resistance was calculated downstream of the inception point of air entrainment for all geometries and discharges.

4.1. Energy dissipation rate and residual head

In the present study, the observations of the rate of energy dissipation $\Delta H/H_{max}$ and of the residual energy H_{res}/d_c at the downstream end of the stepped spillway highlighted the effectiveness of stepped spillway designs with non-uniform step heights. In these expressions, H_{max} is the maximum upstream head above toe $H_{max} = H_{dam} + 3/2 \times d_c$, where H_{dam} is the dam height, ΔH is the total head loss $\Delta H = H_{max} - H_{res}$ and H_{res} is the residual head at the location of measurement:

$$H_{res} = d \times \cos\theta + \frac{U_w^2}{2 \times g} \tag{1}$$

In Eq. 1, the calculations of the equivalent clear water flow depth d and the flow velocity U_w were based upon measurements of the air-water flow with phase detection intrusive probes. The flow depth was defined as

$$d = \int_{y=0}^{Y_{90}} (1 - C) \times dy \tag{2}$$

where Y_{90} is the characteristic depth with C = 90% and C is the air concentration. The flow velocity was $U_w = q_w/d$, where q_w is the water discharge per unit width. Figure 4 illustrates the energy dissipation rate in the present study as a function of a dimensionless expression of the height from the weir crest head to the measured step edge $\Delta z_0/d_c$. For all flow configurations, a decreasing energy dissipation rate with increasing discharge was visible which is consistent with earlier studies on stepped spillways (Matos, 2000; Chanson, 2001b; Felder & Chanson, 2009a). All data sets were in fairly close agreement, but some small differences between the different experimental configurations suggest the largest energy dissipation rate for a uniform spillway with 10 cm high steps. The figure shows clearly that Stephenson's (1988) statement of a 10% increase in energy dissipation for non-uniform step heights was not observed in the present study. However, the differences for uniform step heights of 5 and 10 cm showed some scale effects, which were also observed in earlier studies of stepped spillway flows (e.g. Boes, 2000; Chanson & Gonzalez, 2005; Felder & Chanson, 2009b).

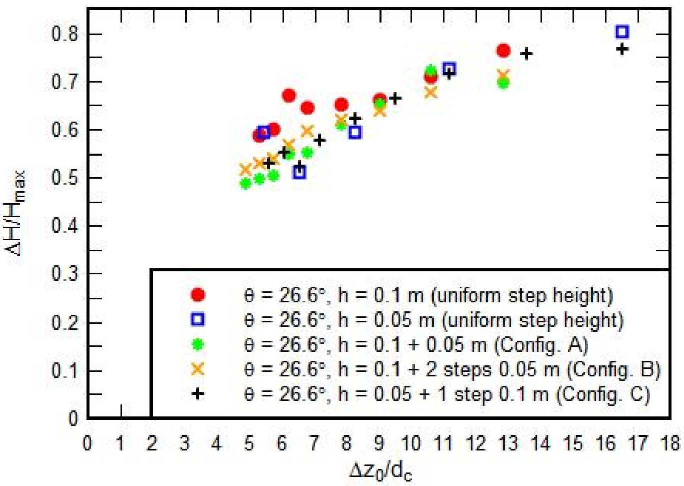

Figure 4 Energy dissipation for different step configurations in the present study; measurements at last step edge at downstream end: *x* = 2.01 m

Similar findings were noted in terms of the dimensionless residual head H_{res}/d_c (Figure 5). The data herein are shown as a function of the dimensionless flow rate d_c/h and compared with some simple design criterion for moderately slopped spillways (Felder & Chanson, 2009b). The present findings agree very well with the data of previous studies with slopes between 3.4 and 26.6º which were used for the median values shown in Figure 5. The upper line expresses the median residual energy for spillway slopes smaller 15.9º and the lower line the median values for stepped spillways with slopes of 21.8 and 26.6º. For the smaller flow rates, the residual head decreased with increasing discharge for all experiments and it remained almost constant for the largest flow rates. However for the largest flow rates, the discharge was not fully developed at the downstream end of the spillway and the residual energy might be overestimated (Chanson, 2001b; Gonzalez & Chanson, 2007b; Felder & Chanson, 2009a). Figure 5 indicates further some scale effects because the residual head for the larger step heights was comparatively smaller. The present findings showed that the residual head for all step configurations was similar and that the configuration with non-uniform step heights did not yield any advantages in terms of energy dissipation performances.

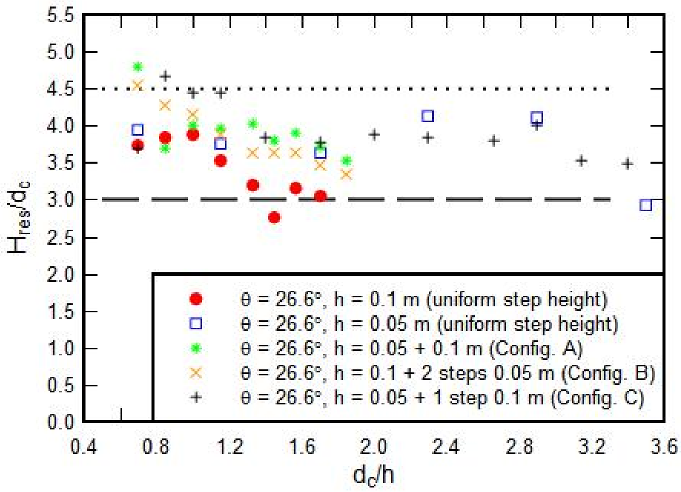

Figure 5 Residual head for different step configurations in the present study; measurements at last step edge at downstream end: *x* = 2.01 m; median values are shown in dotted/dashed lines

4.2. Flow resistance

The flow resistance in skimming flows on stepped spillways is characterised by significant form losses caused by the steps (Chanson, 2001b). The turbulent main stream flow skims over the pseudo-bottom and initiates recirculating vortices in the cavities. In addition to this form drag, energy dissipation is caused by momentum exchanges between mainstream flow and cavity flow and by skin friction at the downstream half of each step. It is common to use the Darcy friction factor f to quantify the flow resistance in skimming flows on stepped spillways (Rajaratnam, 1990):

$$f_e = \frac{8 \times \tau_0}{\rho_w \times U_w^2} = \frac{8 \times g \times S_f \times \left(\int_{y=0}^{Y_{90}} (1-C)\,dy \right)}{U_w^2} = \frac{8 \times g \times S_f \times d}{U_w^2} \tag{3}$$

In the present study, the uniform equilibrium flow was not achieved, and the Darcy friction factor for gradually-varied flow was used where the friction slope equals $S_f = -\partial H/\partial x$, where H is the total head, x is the distance in flow direction and U_w is the flow velocity (Henderson, 1966; Chanson, 2001b). The equivalent Darcy friction factor f_e herein is only valid in the gradually varied flow downstream of the inception point. Figure 6 shows the friction factors of the present study as a function of the dimensionless step roughness height $h \times cos\theta/D_H$, where D_H is the hydraulic diameter. In Figure 6, a comparison with a mixing length model (Eq. 4) is also illustrated. At every step edge, a shear layer develops and the transfer of momentum across the mixing layer drives the cavity recirculation. A simplified analytical model expresses the pseudo-boundary shear stress in dimensionless form:

$$f_d = \frac{2}{\sqrt{\pi} \times K} \qquad (4)$$

where f_d is an equivalent Darcy friction factor estimate of the form drag and $1/K$ is the dimensionless rate of expansion of the shear layer (Chanson, 2001b; Chanson et al., 2002). Brattberg et al. (1998) found in detailed air-water mixing layer experiments in plunging jets that the factor K is best fitted by 6 for a velocity between 2 and 6 m/s.

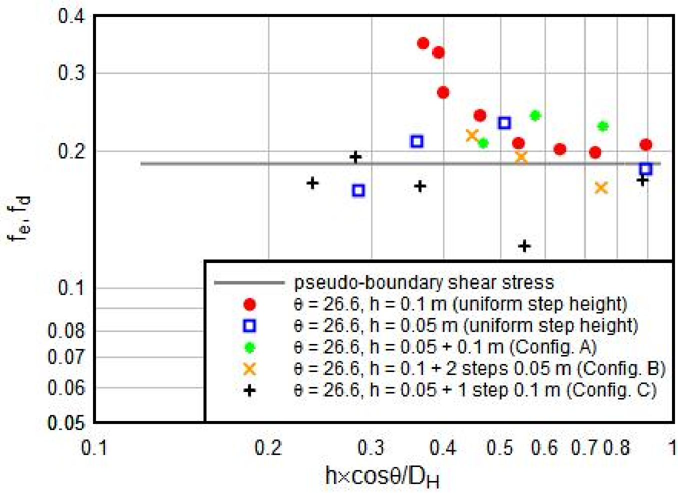

Figure 6 Flow resistance for different step configurations in the present study

The Darcy friction factor varied between 0.12 and 0.37 and was in fairly good agreement with Eq. 4. This observation is consistent with analyses of the flow resistance of different experiments by Chanson et al. (2002) and Felder & Chanson (2009a), with variation of Darcy friction factors between 0.1 and 0.35. In the non-aerated flow region, Amador et al. (2006) observed an average friction factor of 0.125 for d_c/h = 2.1 and Re = 4.4 10^5. The differences in magnitude of the Darcy friction factors may be explained by the different step configurations, but the non-uniform step heights did not indicate any advantageous spillway design. Yasuda & Chanson (2003) showed that the flow resistance value can highly differ depending on the calculated step edge. Another reason might be that for larger discharges the flow may not be fully-developed at the downstream end of the spillway.

4.3. Mean air concentration

A key characteristic of stepped spillway flows is the strong air entrainment and the parameter of mean air concentration $C_{mean} = 1 - d/Y_{90}$ might provide some gross estimate about the aeration performance. C_{mean} was measured at the downstream end and the characteristic values are illustrated as a function of the dimensionless discharge d_c/h in Figure 7. For all spillway configurations, the mean air concentrations were in fairly good agreement and some large levels of air were present at the downstream end. With increasing discharge the air concentration decreased which was simply caused by the reduced length of the aerated flow region. For the smaller discharges, the configurations with the non-uniform step heights showed some larger air concentrations compared to the uniform stepped spillways which might be caused by stronger instabilities of the flow in the transition flow regime. Configurations A and B showed some smaller air concentration levels for larger flow rates compared to the 10 cm uniform spillway. C_{mean} in configuration C was slightly larger for the larger flow rates compared to the uniform 5 cm configuration. The differences in mean air concentration may be explained by the flow disturbances resulting from the different step heights. For smaller flow rates, some flow instabilities were present which caused some larger aeration of the flow. Interestingly, the implementation of some 5 cm high steps in the 10 cm stepped spillway reduced the air entrainment performance for the largest flow rates. The non-uniform configuration C was characterised by transition flows at the downstream end for $d_c/h \le 1.73$ (Table 2) which caused larger air entrainment.

The present findings indicated that the non-uniform step height configurations did not provide any better aeration performance.

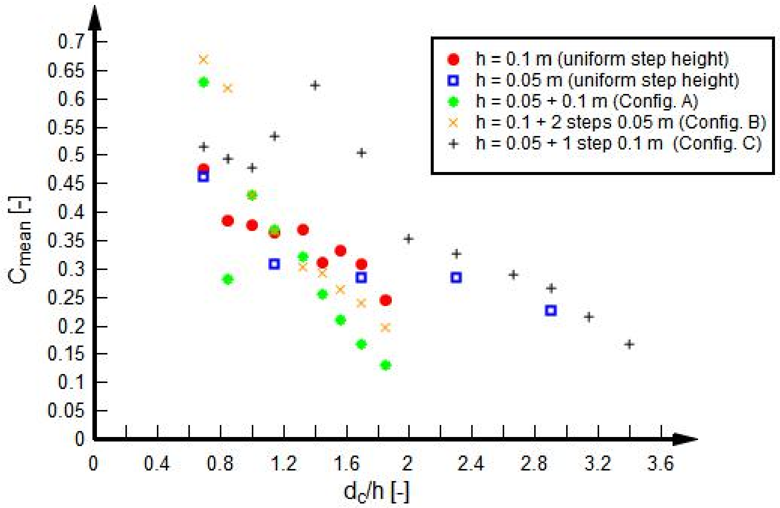

Figure 7 Comparison of mean air concentration C_{mean} for the different configurations; θ = 26.6º; downstream end: x = 2.01 m

4.4. Discussion

The experimental results showed that there were only small differences between all configurations in terms of energy dissipation rate, residual head, flow resistance and mean air concentration. The present results indicated that the design of stepped spillways with non-uniform step heights will not enhance the energy dissipation at the downstream end, contrary to Stephenson's (1988) statement. The present findings highlighted some useful information for alternative designs of stepped spillways for design engineers. The current observations were on a macroscopic level and did not provide insight in the two-phase flow structure. The observations of the flow pattern indicated that the non-uniform configuration might lead to stronger flow instabilities for smaller flow rates, larger flow depth and stronger splashing. It is of special interest to see the effect of non-uniform step heights on the full range of air-water flow properties to identify the aeration performance and the turbulence characteristics. The air-water flows on stepped spillways were affected by scale effects as observed in earlier studies with geometrically scaled models (Boes, 2000; Chanson & Gonzalez, 2005; Felder & Chanson, 2009b). The experimental results of the present study, suggested also some scale effects for the two uniform step geometries of 5 and 10 cm step heights in terms of energy dissipation rate and residual head. For the configurations with non-uniform step heights, some scale effect might be also present along the chute. Some further data analyses at all step edges downstream of the inception point are required to allow a better comparison of the different channel geometries and to investigate possible scale effects.

5. CONCLUSION

An experimental study was conducted on a stepped spillway model with a slope of 26.6º and with various configurations of uniform and non-uniform step heights of 5 and 10 cm. The flow pattern was observed. In the air-water flow region at the downstream end of the spillway, the characteristic two-phase flow properties were measured with a double-tip conductivity probe. For the spillway configurations with non-uniform step heights, the experiments provided a unique data set which might be used for design guidelines for prototype stepped spillways with various spillway heights. A comparative analysis with uniform channels showed very little differences with non-uniform step height configurations in terms of energy dissipation rate, residual head, flow resistance and mean air concentration.
For design engineers, the present findings highlighted that the stepped spillways design with uniform

step heights is the preferred design option. While the combination of different step heights provides a similar rate of energy dissipation, the flow might be affected by some instabilities, and the final design should be tested with some thorough physical modeling.

6. REFERENCES

Amador, A., Sanchez-Juny, M. and Dolz, J. (2006), *Characterization of the Nonaerated Flow Region in a Stepped Spillway by PIV,* J Fluid Eng, 128 (6), 1266-1273

Boes, R.M. (2000), *Zweiphasenströmung und Energieumsetzung an Grosskaskaden*. (*Two-Phase Flow and Energy Dissipation on Cascades*.); Ph.D. thesis, VAW-ETH, Zürich (in German)

Brattberg, T., Chanson, H. and Toombes, L. (1998), *Experimental Investigations of Free-Surface Aeration in the Developing Flow of Two-Dimensional Water Jets*, J Fluid Eng, 120 (4), 738-744

Chanson, H. (2001a), *Hydraulic Design of Stepped Spillways and Downstream Energy Dissipators*, Dam Engineering, 11 (4), 205-242

Chanson, H. (2001b), *The Hydraulics of Stepped Chutes and Spillways*, Balkema, Lisse

Chanson, H. (2002), *Enhanced Energy Dissipation in Stepped Cutes. Discussion*, in *Proceedings of the Institution of Civil Engineers Water & Maritime Engineering*, 154 (4), 343-345

Chanson, H. and Carosi, G. (2007), *Turbulent time and length scale measurements in high-velocity open channel flows*, Exp Fluids, 42 (3), 385-401

Chanson, H. and Gonzalez, C.A. (2005), *Physical modelling and scale effects of air-water flows on stepped spillways.*, Journal of Zhejiang University SCIENCE, 6A (3), 243-250

Chanson H., Yasuda, Y. and Ohtsu, I. (2002), *Flow Resistance in Skimming Flows and its Modelling*, Can J Civil Eng, 29 (6), 809-819

Felder, S. and Chanson, H. (2009a), *Energy dissipation, flow resistance and gas-liquid interfacial area in skimming flows on moderate-slope stepped spillways*, Environ Fluid Mech, 4 (9), 427-441

Felder, S. and Chanson, H. (2009b), *Turbulence, Dynamic Similarity and Scale Effects in High-Velocity Free-Surface Flows above a Stepped Chute*, Exp Fluids, 47 (1), 1-18

Gonzalez, C.A. (2005), *An Experimental Study of Free-Surface Aeration on Embankment Stepped Chutes.*, Ph.D. thesis, Department of Civil Engineering, The University of Queensland, Brisbane

Gonzalez, C.A. and Chanson, H. (2007a), *Experimental Measurements of Velocity and Pressure Distribution on a Large Broad-Crested Weir*, Flow Meas Instrum, 18 (3-4), 107-113

Gonzalez, C.A. and Chanson, H. (2007b), *Hydraulic Design of Stepped Spillways and Downstream Energy Dissipators for Embankment Dams*, Dam Engineering, 17 (4), 223-244

Henderson, F.M. (1966), *Open Channel Flow*, MacMillan Company, New York

Matos, J. (2000), *Hydraulic Design of Stepped Spillways over RCC Dams*, in Minor, H.E. and Hager, W.H. (Eds) *Proceedings of the international workshop on hydraulics of stepped spillways,* Zürich, March 22-24, 2000, pp. 187-194

Rajaratnam, N. (1990), *Skimming Flow in Stepped Spillways*, J Hydraul Eng-ASCE, 116 (4), 587-591

Stephenson, D. (1988), *Stepped Energy Dissipators,* in *Proceedings of the International Conference on Hydraulics for High Dams*, Beijing, November 15-18, 1988, pp. 1228-1235

Thorwarth, J. and Köngeter, J. (2006), *Physical Model Test on a Stepped Chute with Pooled Steps – Investigation of Flow Resistance and Flow Instabilities*, in Marcano, A. et al. (Eds), *Proceedings of the International symposium on Hydraulic Structures*, Cuidad Guayana, October 2006, pp. 477 - 486

Toombes, L. (2002), *Experimental Study of Air-Water Flow Properties on Low-Gradient Stepped Cascades*, Ph.D. thesis, Dept. of Civil Engineering, University of Queensland, Brisbane

Toombes, L. and Chanson, H. (2008), *Flow patterns in nappe flow regime down low gradient stepped chutes*, J Hydraul Res, 46 (1), 4-14

Yasuda, Y. and Chanson, H. (2003), *Micro- and Macro-scopic Study of Two-Phase Flow on a Stepped Chute*, in Ganoulis, J. and Prinos, P. (Eds). *Proceedings of the 30th IAHR Biennial Congress*, Thessaloniki, 24–29 August, 2003, pp. 695-702