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Hydraulics and Energy Dissipation on a Steep Stepped Spillway: Physical Modelling in a Large-size Facility

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ABSTRACT

During the last five decades, a number of overflow stepped spillways were built because the staircase bywash shape is conducive to reduced construction costs and increase rate of energy dissipation. Stepped spillways are characterised by highly turbulent air-water flows and a large rate of energy dissipation compared to smooth chutes. Herein, detailed measurements were performed in a large-size 1V:0.8H stepped spillway model, with a steep slope typical of modern concrete gravity dams. Detailed two-phase flow measurements were conducted to characterise finely the self-aeration and air diffusion process downstream of the inception region of free-surface aeration. The bubble count rate profiles scaled with the instantaneous void fraction variance, yet the relationship was biased close to the invert under the influence of large-scale coherent structures. The rate of energy dissipation was calculated based upon the two-phase flow measurements and the results are compared with earlier result on similar steep invert slopes. At the downstream end of the stepped chute, the rate of energy dissipation ranged from 43% to 46%, more than twice that on a smooth-invert chute for a similar chute length and discharge range.

INTRODUCTION

Dams are equipped with spillway structure(s) to discharge excess flood water during major rainfall and runoff events (USBR 1965, Novak et al. 2007). A sound spillway design allows both the safe conveyance of flood waters and the safe dissipation of the overflow kinetic energy, before the spill waters rejoin the natural stream channel. During large floods, the rate of energy dissipation can be astonishing and exceeds the electrical outputs of large nuclear power plants (Chanson 2015). With chute spillways, the design may incorporate macro-roughness along the steep chute, such as a staircase invert, to reduce the size of the downstream energy dissipator (Sorensen 1985, Chanson 1995, Boes and Hager 2003). Figure 1 illustrates some overflow stepped spillways installed on concrete gravity dams.

Stepped spillways and wastewaterways have been in use for several millennia (Chanson 2001). During the 19th and early 20th centuries, a sizeable amount of dam spillways were designed with a stepped profile worldwide, including in Australia, e.g. Gold Creek Dam, Malmsbury Dam, Goulburn weir (Chanson and Whitmore 1998). For the past 50 years, the advancement in dam construction technology, e.g. Roller Compacted Concrete (RCC) and Immersion Vibrated Roller Compacted Concrete (IVRCC), led to a strong interest for the stepped spillway design with concrete gravity structures. Figure 1 presents two RCC gravity dams equipped with a stepped spillway. Further, the combination of some re-evaluation of the Probable Maximum Flood (PMF) magnitude and local geographical constraints at the dam site can favour the stepped design, e.g. Hinze Dam Stage 3.

In the last 20 years, a number of stepped spillway laboratory studies were conducted with chute slopes ranging from 1V:3.5H to 1V:1H (Chanson and Toombes 2002, Gonzalez 2005, Bung 2009, Felder 2013, Zhang 2017, Arosquipa Nina et al. 2022). In this contribution, new physical measurements were conducted in a large-size stepped spillway model, with a chute slope (1V:0.8H) typical of modern concrete gravity dams. Detailed two-phase flow measurements were conducted to finely characterise the self-aeration, the air-water flow properties and the rate of energy dissipation.

(A)

(B)

Figure 1. Concrete gravity dams equipped with stepped spillway: (A) Pedrogao Dam, Portugal (1V:0.75H slope) on 4 September 2006; (B) Riou Dam, France (1V:0.6H slope) on 11 February 2004.

EXPERIMENTAL METHODS AND INSTRUMENTATION

The experiments were conducted in a new stepped spillway physical model (1V:0.8H) located in the Advanced Engineering Building (AEB) at the University of Queensland (UQ). Three adjustable altering currents (AC) pumps delivered the flow into the 1.7 m deep and 5 m wide concrete basin. The water was smoothly converged by a 2.8 m long symmetrical sidewall profile before entering the 0.985 m wide test section surrounded by glass sidewalls. The long concrete sidewall convergent with a contraction ratio of 5.08:1 resulted in a smooth and waveless flow into the upstream broad-crested weir (Chaokitka and Chanson 2022). The weir was followed by a 1.4 m high stepped chute, with step height h = 0.10 m and step length l = 0.08 m (Figs. 2 & 3 Right).

The water discharge was deduced from measured upstream head above crest using discharge calibration results of Chaokitka and Chanson (2022). The upstream water depth was measured using a MeasumaX™ Single Column Digital Height gauge with an accuracy of ±0.05 mm. Clear-water flow depths were measured with a pointer gauge on the channel centreline. The air-water flow properties were recorded with a dual-tip phase-detection conductivity probe. The dual-tip probe was equipped with two identical needle sensors with an inner diameter of 0.25 mm and a separation of probe tips Δx_{tip} = 9.0 mm in the longitudinal direction. Each probe sensor was sampled at 20 kHz for 45 s based upon previous sensitivity analysis results (Felder 2013, Zhang 2017). The profiles of air-water flow properties were recorded at different cross sections with a range of flow conditions. Each vertical profile contained a minimum of 20 to 30 points on the channel centreline. The translation of the dual-tip phase-detection probe in the vertical direction was measured by a Mitutoyo™ digital scale unit with an accuracy of ±0.025 mm.

The dual-tip phase-detection signal outputs were post-processed using a single threshold technique set at 50% of the voltage difference between air and water (Cartellier and Achard 1991, Toombes 2002), thus assigning an instantaneous void fraction value of 1 for air and of 0 for water. The time-averaged void fraction was equal to the average time spent by the probe sensor in air relative to the total time. The bubble count rate was defined as the number of detected particles per unit time. The air-water interfacial velocity was derived from a cross-correlation technique, based upon the time lag corresponding to the maximum cross-correlation coefficient between leading and trailing tip signals (Cain and Wood 1981, Chanson 2002).

General observations were conducted for unit discharges between 0.002 m^2/s and 0.195 m^2/s. Detailed air-water flow measurements were performed in the stepped spillway for three different water discharges, corresponding to dimensionless discharges d_c/h = 1.0, 1.33 and 1.56, with d_c the critical flow depth ($d_c = (q^2/g)^{1/3}$), q the unit discharge, g the gravity constant and h the vertical step height. These flow conditions corresponded to some skimming flow with Reynolds numbers Re = 3.8×10^5, 6.1×10^5 and 7.8×10^5 respectively.

RESULTS

Basic flow patterns

At low flow rates corresponding to $d_c/h < 0.45$, the water flowed down the chute as a series of free-nappes without hydraulic jump. For $0.45 < d_c/h < 0.9$, the overflow discharge was highly turbulent, with very strong splash and intense spray, i.e. a transition flow. For dimensionless discharges $d_c/h > 0.9$, the flow skimmed over the pseudo-bottom formed by the step edges and the streamlines were approximately parallel to the invert. As the boundary layer formed further downstream, the free surface features varied largely. The turbulent shear stresses operating close to the free surface dominated over the combined effects of surface tension and buoyancy when the outer edge of the forming boundary layer reached the free surface region, leading to air entrainment (Ervine and Falvery 1987, Zabaleta et al. 2020). Close inspection of the cavity vortices revealed irregular ejection of fluid from the cavity into the mainstream towards the upper portion of the vertical step face, as well as replacement of cavity fluid along the step edge, indicating a high degree of mainstream-cavity interaction, as noted by Rajaratnam (1990) and Chanson (2001). The flow was self-aerated downstream of the region where free-surface aeration began, and the air-water flow measurements revealed that the velocity profiles were fully-developed.

Visually, the laboratory flow conditions were similar to prototype observations on 1V:0.8H stepped spillways, as illustrated in Figures 2 and 3; the geometric scaling ratio beween prototype and model was 15:1 in both figures. For two dimensionless discharges d_c/h, the photographs present a side-by-side comparison of laboratory and prototype stepped spillway flows with the same chute slope (Figs. 2 & 3). The main visual differences were (a) the dark brown colour of the protoype flow at the upstream end, and (b) the intense air-water turbulence in the self-aerated flow region of the prototype spillway The former indicated some sediment-laden inflow into the spillway. The latter might hint for a more dynamic air entrapment process in the prototype implying that the air bubble diffusion process in laboratory was not in similitude with that in large prototype spillways. This aspect was previously argued and highlighed by Zhang and Chanson (2017).

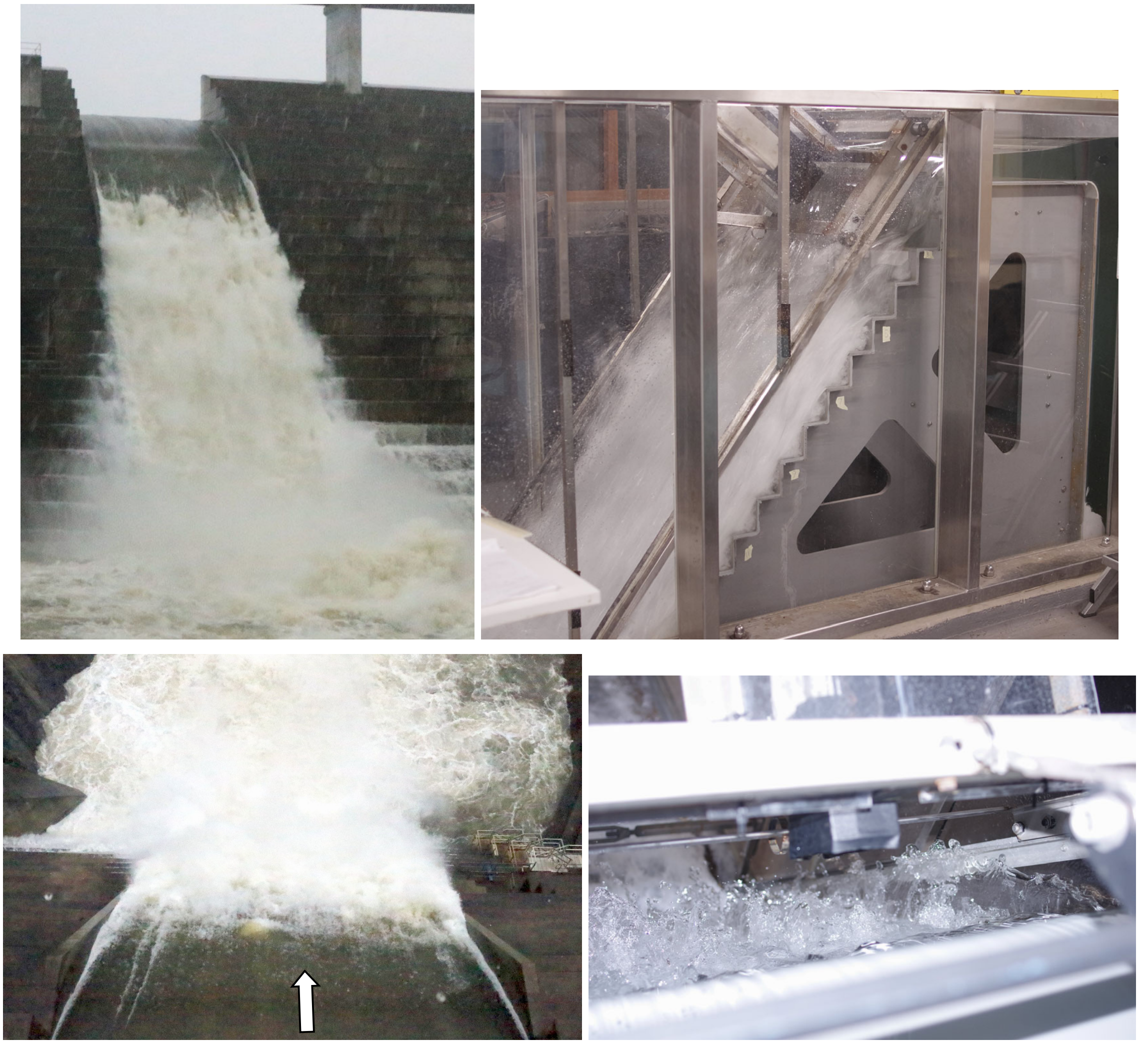

Figure 2. Prototype and laboratory model stepped spillways (1V:0.8H) in operation for $d_c/h = 1$ - Left: Hinze Dam spillway operation on 26 February 2022 (photograph taken under heavy rainfall); Right: laboratory model

Figure 3. Prototype and laboratory model stepped spillways (1V:0.8H) in operation for d_c/h = 1.6 - Left: Hinze Dam spillway operation on 3 March 2022 (photograph taken under light to heavy rainfall); Right: laboratory model

Air-water flow properties

The air-water flow property measurements were conducted at all step edges downstream of the inception region of free surface aeration. In the direction normal to the flow, measurements were obtained above the pseudo-bottom formed by the step edges up to the upper spray area. The void fraction profiles followed a S-shape, illustrated in Figure 4A. The void fraction data implied the strong flow aeration and fragmentation of the skimming flow regime, with increasing aeration with increasing distance downstream of the inception region of free-surface aeration. The bubble count rate profiles scaled with the instantaneous void fraction variance, reaching a maximum for void fraction between 0.35 and 0.5 (Fig. 4B). The relationship between bubble count rate and void fraction presented a pseudo-parabolic shape, altough it was biased close to the invert under the influence of large-scale coherent structures. All the data showed an increasing maximum bubble count rate with increasing downstream distance, without reaching an asymptotic value. The finding implied that the air-water structure typology, and the bubble-turbulence intereactions, continued to evolve and did not reach an equilibrium. This longitudinal pattern was observed in earlier studies (e.g. Boes 2000, Yasuda and Chanson 2003) and might be linked to scaling issues (Felder and Chanson 2009).

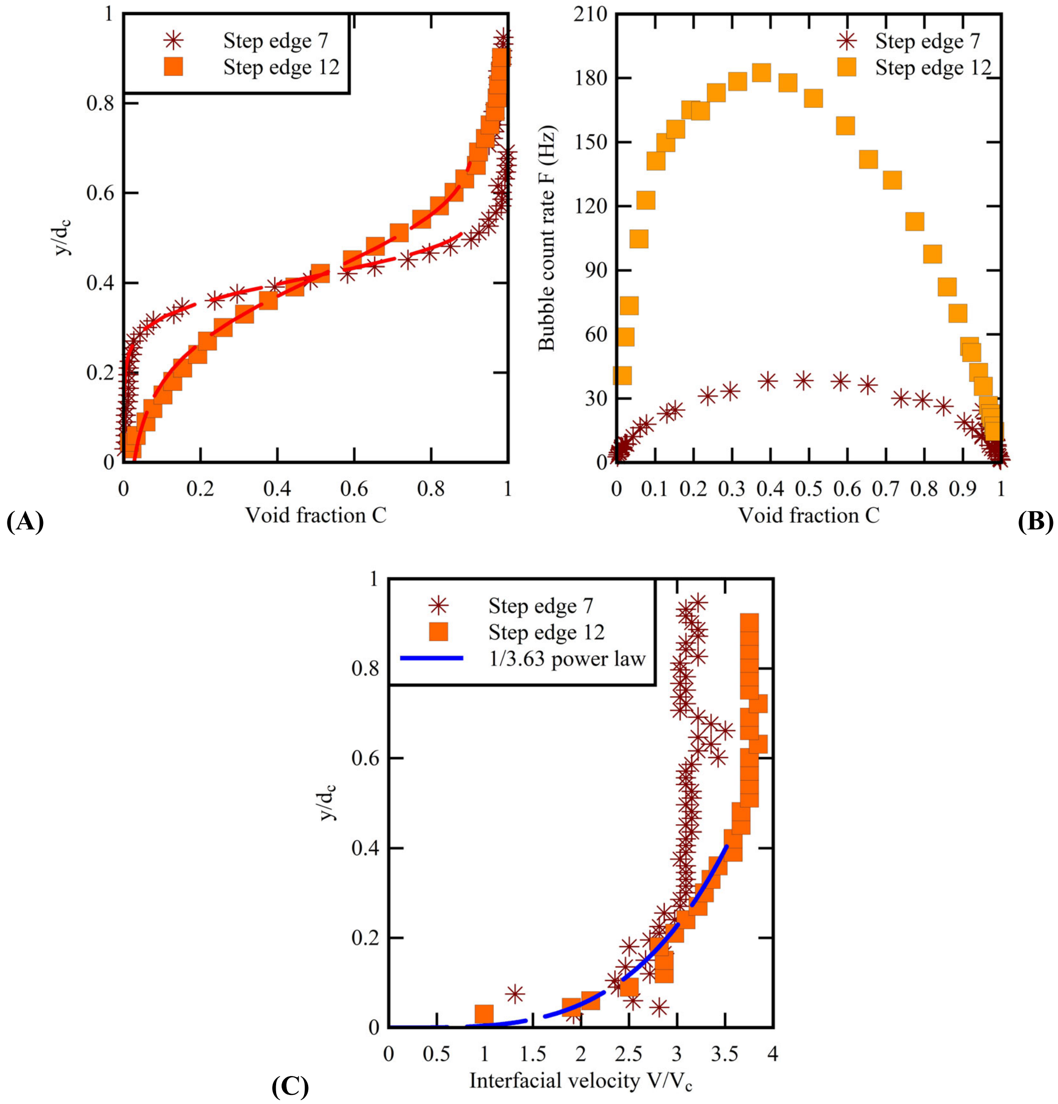

Figure 4. Air-water flow properties in the large-size laboratory model stepped spillway (1V:0.8H) for d_c/h = 1.33 and Re = 6.1×10^5 - (A) Void fraction profiles: comparison between data and theoretical solution (Chanson and Toombes 2002) [dashed line]; (B) Bubble count rate versus void fraction relationship; (C) Interfacial velocity profiles: comparison between data and power law [dashed line]

The air-water velocity profiles showed a power law for void fractions less than 0.9 (Fig. 4C). The power law exponent 1/N varied between 1/3.5 and 1/6, in line with experimental observations in steep stepped spillway models by Matos (1999,2000) [1V:0.75H] and Boes (2000) [1V:0.84H]. In contrast, observations on embankment dam spillway models yielded a velocity power law exponent 1/N between 1/7 and 1/12 (Gonzalez 2005, Bung 2009, Felder 2013). The difference in velocity profile shape was very likely linked to differences in momentum transfer between the main flow and the cavity region, together with different step cavity recirculation patterns and processes, between steep concrete gravity dam and embankment dam stepped spillways.

DISCUSSION

In a skimming flow on a steep stepped spillway, the dissipation of the kinetic energy is primarily driven by the cavity recirculation in the stepped cavities and associated form drag. Both the fluid accceleration and boundary layer development in the non-aerated region affect the rate of energy dissipation. In the present study, the rate of energy dissipation was estimated, taking into account the air-water flow properties inclusive of the air-water pressure and velocity correction coefficients (Arosquipa Nina et al. 2022). At the downstream end of the stepped spillway, the rate of energy dissipation ranged from 43% to 46%, with the rate of energy dissipation being the ratio of total head loss to upstream total head. In comparison, for a similar chute length and discharge range, the rate of energy dissipation on a steep smooth invert would be about 20% (Bradley and Peterka 1957). The present data are further reported in Figure 5 in terms of the dimensionless residual head H_{res}/h as a function of the dimensionless drop in invert elevation $\Delta z_o/h$. In Figure 5, the experimental data are compared to the design calculations of Matos (2000) for steep concrete gravity dam stepped spillways. The results may be used to estimate the residual head for a step height, spillway given height and design unit flow.

Altogether, the present data showed an increasing residual head with increasing discharge, linked to the further downstream location of the inception region at larger discharges. For much larger discharges, the steep chute free-surface flow would become non-aerated, and the flow would not be fully-developed before the downstream end of the spillway. The residual head would be significantly larger and a different design calculation method would be required, e.g. Chanson (2001), Gonzalez (2005).

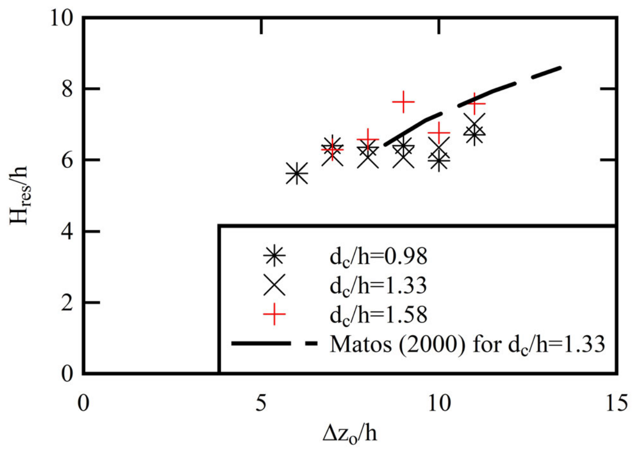

Figure 5. Dimensionless residual energy at the steep stepped spillway model (1V:0.8H) taking into account the air entrainment - Comparison with the design method of Matos (2000)

CONCLUSION

The present study investigated the hydraulics of a steep stepped spillway with a 1V:0.8H slope, typical of concrete gravity dam designs. The goal of this project was to accurately estimate the hydrodynamics, interfacial aeration, and energy dissipation of a steep stepped stream in a large-size facility. The upstream flow motion was non-aerated in skimming flow regime and the free-surface appeared reasonably smooth up to the inception region of free-surface aeration. Downstream, the surface became extremely turbulent and strong air entrainment was observed in the physical model. The observations were consistent with prototype observations for Froude-similar flow conditions and identical slope.

Detailed air-water flow measurements were performed on the step edges downstream of the region when the free-surface aeration occurred. The data demonstrated consistent patterns in skimming flow regimes, despite quantitative variations. The void fraction distribution compared well with theoretical models. The relationship between void fraction and bubble count rate presented a quasi-parabolic shape skewed towards the invert. The velocity profiles tended to follow a power law, with an exponent typical of steep stepped spillways, which differed from observations on embankment dam stepped spillways.

The rate of energy dissipation and residual energy data are presented for fully-developed air-water flows on steep stepped spillways, showing a massive increase in rate of energy dissipation along tbe steep chute compared to smooth-invert chute flows: i.e. more than twice that on a smooth-invert chute for a similar chute length and discharges. It is acknowledged that, for very large discharges, the flow might not be fully-developed at the downstream end of the steep chute and a different design approch would be necessary, for both smooth- and stepped-invert chutes.

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BIOGRAPHY

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Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-8 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,350 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/@Hubert_Chanson}.