CHANSON, H. (2021). "Hydraulics and Energy Dissipation on Stepped Spillways - Prototype and Laboratory Experiences." *Proceedings of the 2nd International Symposium of Advances in Water Disaster Mitigation and Water Environment Regulation WDWE2021,* July 7-9, Chengdu, China, Sichuan University Press, **Invited Plenary Keynote Paper**, pp. 1-15 (ISBN 978-7-5690-4817-9).

Hydraulics and Energy Dissipation on Stepped Spillways-prototype and Laboratory Experiences

Hubert Chanson

The University of Queensland, School of Civil Engineering, Brisbane QLD 4072, Australia

Abstract

Stepped spillways are used since more than 3, 000 years. With the introduction of new construction materials(e. g. RCC, PVC coated gabions), the stepped spillway design has regained some interest for the last five decades. The steps increase significantly the rate of energy dissipation taking place along the chute, thus reducing the size of the required downstream energy dissipation basin. Stepped cascades are used also for in-stream re-aeration and in water treatment plants to enhance the air-water transfer of atmospheric gases and of volatile organic components. Yet the engineering design stepped spillways is not trivial because of the complicated hydrodynamics, with several possible, distinctly different flow regimes, complex two-phase air-water flow motions and massive rate of energy dissipation above the staircase invert. Altogether, the technical challenges in hydraulic engineering and design of stepped spillways are massive. This keynote lecture reviews the hydraulic characteristics of stepped channel flows and develops a reflection on nearly 30 years of active research including recent field measurements during major flood events. The writer aims to share his passion for hydraulic engineering, as well as some advice for engineering professionals and researchers.

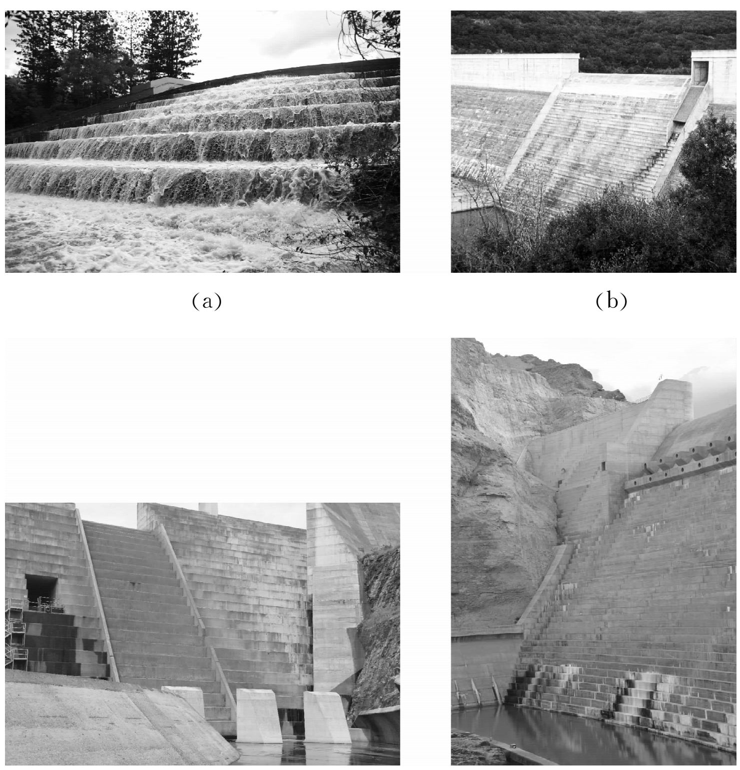
Keywords: Stepped spillways; Hydraulic modelling; Field measurements; Energy dissipation and design; Multiphase air-water flows

1 Introduction

Extreme fluid flow events, and structures interacting with them, are critical for a wide range of areas, including reliability and design in engineering, as well as evaluation of cost-effectiveness of projects and optimisation of investments. Flooding is the most frequently occurring natural disaster in the world and has been increasing during the last two decades at an alarming rate(UNDRR 2019). It is expected that extreme flooding will occur even more frequently as a result of climate change(Rojas et al. 2013). In addition to the expected increase in the magnitude and frequency of future flooding, there will also be an increase in the world's population from the current level of 7.7 billion to 9.7 billion by 2050. Within this context, losses of life, and exorbitant aftermath damage costs will continue unless significant steps are taken to prevent catastrophic failures of critical infrastructure, in the face of pressures such as population growth, catchment development and climate change.

In spite of the continuous hydrological cycle of water, the rainfall pattern on our planet is not uniform, with more and more countries being subjected to hydrological extremes(floods, droughts) with high spatial and temporal variability. The catalogue of the world's maximum floods highlighted some astonishing record flow rates (IAHS 1984). In contrast, many regions have experienced recurrent long droughts for the last 300 years, e.g. Africa, Australia, Central Asia. Today, man-made reservoirs and dams are one of the most efficient means to deliver long-term reliable water reserves, as well as flood protection. During major flood events, the floodwaters must be passed safely above, beneath or beside the dam: this is achieved with a spillway system, a water system designed to discharge safely the extreme reservoir outflows (USBR 1965, Novak et al. 1996). In terms of fluid dynamics, the main functions of a spillway are the safe conveyance of floodwaters and energy dissipation. The dissipation of the spill's kinetic energy takes place down the steep chute and at the downstream end of the spillway system, and the amount of kinetic energy dissipation can be truly astonishing (Chanson 2015, pp. 5 − 8). Energy dissipation at dam spillways can take place in a hydraulic jump stilling structure, with a ski jump, a plunge pool, an impact dissipator, the installation of macro-roughness on the spillway chute, or a combination of the above (Vischer and Hager 1995, Chanson 2015). In modern times, the simplest type of macro-roughness is the installation of steps, that can be relatively easily accommodated during construction with several construction materials (Chanson 1995, 2001) (Fig. 1).

In this paper, it is argued that the hydraulic design stepped spillways is not trivial because of the complicated hydrodynamics and massive rate of energy dissipation above the staircase invert. The technical challenges are discussed, in the light of the state-of-the-art into stepped spillway hydraulic research and practice, including recent field observations during major flood events.



(a) (b) (c) (d)

Figure 1. Stepped spillways

Note: (a) Gold Creek Dam (Australia, 1890) on 23 February 2015; (b) Les Olivettes Dam (France, 1987) in March 2003 (Courtesy Mr & Mrs J. Chanson); (c) Hinze Dam Stage 3 (Australia, 2011) on 26 September 2018; (d) Wadi Dayqah Dam (Oman, 2012) in January 2018 (Courtesy Dr D. Wűthrich).

2 Stepped Spillway and Hydraulics

2.1 Presentation

Stepped spillways have been built and used for several millenia(Chanson 2000—2001). During the 19th century and early 20th century, a significant number of dams were equipped with a "staircase bye wash", i.e. a stepped spillway [Fig. 1(a)] (Wegmann 1911), until the mature design development of the hydraulic jump stilling basin at the toe of smooth chutes. In the last five decades, the advancement in construction technology, e.g. roller compacted concrete (RCC), and the geographic constraints of several dam sites, have driven a renewed interest in the stepped spillway design [Figs. 1(b)(c)(d) and 2]. The steps act as macro-roughness, increasing substantially the rate of kinetic energy dissipation along the spillway chute, in turn reducing the size and cost of the downstream stilling system(Sorensen 1985, Rajaratnam 1990).

A key feature of stepped spillway design is the broad diversity of applications, construction materials and design flow rates. The stepped invert design may be applied to re-aeration cascades, embankment overtopping protection systems, sabo check dams, storm waterways, low-head weirs as well as large concrete dam spillways. The construction of the steps maybe undertaken with timber cribs, gabions and Reno mattresses, precast concrete blocks, roller compacted concrete and conventional concrete blocks. There are further a very wide range of design unit discharges, from less than 0.1 m^2/s to more than 100 m^2/s! Importantly, each stepped chute operation is characterised by some complicated hydrodynamics which requires a high level of hydraulic expertise.

In the next sections, the author will share some thoughts in the challenges associated with the hydrodynamics and hydraulic design of stepped spillways, based upon his 30 years of experiences on the topic. These add an earlier very-relevant keynote paper(Matos and Meireles 2014) and a small number of relevant seminal papers(Bombardelli 2012, Chanson 2013a, Chanson et al. 2021). The writer initially developed an interest for stepped chute hydraulics for pedagogical interests, as part of the postgraduate teaching of hydraulic structures, before developing a strong research focus on physical modelling(Table 1), multiphase flow analyses and hydraulic design(Chanson 1995, 2001, Chanson et al. 2015).

Figure 2. Strong turbulence and intense free-surface aeration in a skimming flow on a stepped spillway

Note: Paradise Dam spillway operation on 5 March 2013 for Q=2,320 m^3/s, d_c/h=2.85, h=0.62 m.

Table 1. Stepped spillway research at the University of Queensland. Characteristics of physical facilities(1995—2021)

q(°)	h(m)	B(m)	q(m^2/s)	Step configuration	Others
2.6	0.143	0.25	0.07～0.14	Single drop	
3.4	0.0715～0.143	0.50	0.038～0.163	Flat horizontal	
3.4	0.0715～0.143	0.50	0～0.075	Flat horizontal	Dam break wave

(To be continued)

(Continue)

q(°)	h(m)	B(m)	q(m²/s)	Step configuration	Others
15.9	0.05~0.10	1.0	0.020~0.26	Flat horizontal	
21.8	0.05~0.10	1.0	0.008~0.19	Flat horizontal	
21.8	0.10	1.0	0.10~0.219	Triangular vanes	
21.8	0.10	1.0	0.01~0.241	Rough steps	
26.6	0.10	0.52	0.005~0.241	Flat horizontal	
26.6	0.10	0.52	0.003~0.282	Pooled steps	
26.6	0.10	0.52	0.038~0.28	Gabion steps	
45	0.10	0.985	0.001~0.30	Flat horizontal	
45	0.10	0.985	0.083~0.216	Trapezoidal cavities	
45	0.10	0.985	0.0008~0.28	Inclined steps	
51.3	1.5	12.25	5.8~27.3	Flat horizontal	Hinze Dam Stage 3

Notes: q: longitudinal chute slope; h: vertical step height; B: chute width; q: unit discharge.

2.2 Stepped chute hydraulics and its challenges

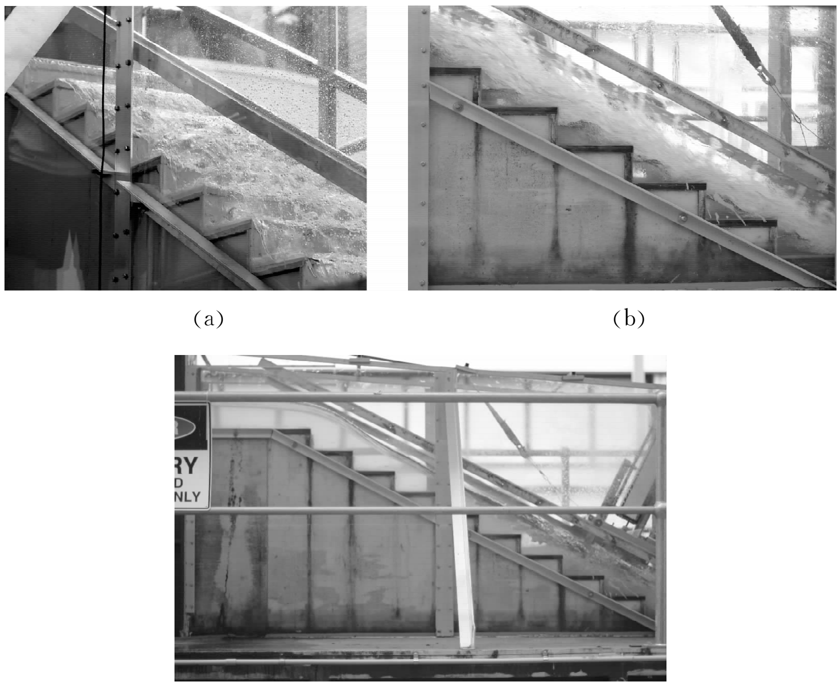
The fluid mechanics of stepped spillway overflow is a very complicated topic (Horner 1969, Peyras et al. 1992, Chanson 1994). The challenges include (a) the strong turbulence and intense free-surface aeration, (b) the existence of markedly different flow regimes on a given stepped geometry, depending upon the unit discharge, and (c) the underlying limitations of both physical modeling and numerical modelling.

First, the stepped chute profile generates some intense turbulent dissipation during the spill associated with a significant kinetic energy dissipation, as well as strong self-aeration through the free-surface (Fig. 2) (Chanson and Toombes 2003, Boes and Hager 2003, Biethman et al. 2021). The steps are conducive to the development of strong cavity recirculation motion. At large discharges, the recirculation motion is maintained through the "pseudo-continuous" transfer of momentum from the main flow to the stepped cavity flow region, in the form of cavity ejection and replenishment process occurring irregularly (Chanson et al. 2002, Toro et al. 2017). The large-scale vortices are shed from the step cavities into the mainstream, before interacting with the free surface (Toro et al. 2017, Chanson 2021). The very strong free-surface turbulence induces a two-phase air-water free-surface mix, since neither gravity nor surface tension can maintain the free-surface cohesion (Ervine and Falvey 1987, Brocchini and Peregrine 2001, Chanson 2009). Visually, large amount of fluid ejections are seen, with complicated air-water structure ejections, and re-attachments further downstream, while the fluid ejections are accompanied with air entrapment. The violent process, i.e. 'eruptions' of air-water masses, is believed to be caused by the collision of tilted powerful large-scale streamwise vortices with the upper surface. In prototype, the upper free-surface may further be the locus of "surface waves", e.g. illustrated at Chinchilla weir (Australia) and Three-Gorges Project (China) (Toombes and Chanson 2007).

Second, the stepped chute flow may be one of several distinct flow regimes, for a fixed stepped geometry, depending upon the water discharge. For a rectangular prismatic channel equipped with flat horizontal impervious steps, the overflow is anappe flow at low unit discharges[Figs. 1(a) & 3(a)], a transition flow for a range of intermediate flow rates [Fig. 3 (b)] or a skimming flow at larger discharges[Figs. 2 & 3 (c)]. The nappe flow regime is typically designed for in older spillway structures built during the 19th century, and it corresponds to small unit discharges (Horner 1969, Chamani and Rajaratnam 1994). The transition flow regime is characterised by hydrodynamic instabilities and chaotic flow conditions, which should be avoided during wastewater spills unless at small flows (Chanson and Toombes 2004). The skimming flow is commonly observed in concrete gravity dam stepped spillways (Sorensen 1985, Matos 1999). Each flow regime has very different features and characteristics from one another (Fig. 3). More complex stepped geometries might have more than three flow regimes, e. g. four flow regimes were reported in gabion stepped chutes (Wüthrich and Chanson 2014), with stationary and instationary motions on pooled stepped spillways (Felder and Chanson 2014).

Third, the hydraulic modelling has been traditionally conducted based upon physical laboratory experiments, designed based upon a Froude similarity (Novak and Cabelka 1981, Sorensen 1985). The upscaling of the laboratory results may be affected by significant scaling issues, with the usage of small-size laboratory facilities. Recent works suggested that the laboratory testing must be conducted at large Reynolds numbers, i. e. $Re > 10^5$ to 5×10^5, to minimise potential scale effects, although scaling issues cannot be eliminated totally unless working at full scale (Chanson and Gonzalez 2005, Felder and Chanson 2009). In turn, the pre-requisite utilisation of large-size laboratory facilities operating with relatively large discharges may be economically expensive (Fig. 4). Free-surface aeration in such large laboratory flumes imply the needs for multiphase flow metrologies, with expensive fine instrumentation, operated by expert researchers. The requirement in human resources cannot be under-stated nor its cost under-estimated, considering that civil engineering undergraduate and postgraduate students are not taught about multiphase fluid dynamics. As an illustration, the author would educate and train a new research student for 2 to 6 months, before he/she can conduct reliable air-water flow measurements of acceptable quality.

Fourth, another form of modelling is the computational fluid dynamics CFD numerical modelling. CFD modelling is based upon the numerical integration of the time-dependent Navier-Stokes equations (Rodi et al. 2013, Rodi 2017). For the last three decades, some novel works developed some multiphase-dedicated CFD models (Prosperetti and Tryggvason 2009, Lubin 2021). The general equations for two-phase flows may be applied to hydraulic structures and stepped spillways (Bombardelli 2012). Yet, not all the results are equal, not all the outputs correct. Too often, the CFD modelling is not validated or incorrectly validated, leading to quantities of physically meaningless results. (As a journal editor and senior expert reviewer, the author has read too many erroneous CFD studies with wholly meaningless data outputs.). Although the AIAA and ASME developed clear guidelines for verification and validation (AIAA 1994, Roache 1998, Rizzi and Vos 1998), these are rarely applied rigorously in hydraulic engineering! There is further a lack of detailed laboratory data sets of high quality and of field observations, most relevant to CFD validation. This is not trivial. Indeed, the physical experiments do not provide all the detailed informations at all spatio-temporal scales, required for CFD model validation. There is no doubt that the potential applications of CFD to stepped spillway hydrodynamics offers a large interest, once it will be properly validated. Further, nearly all the CFD modelling is conducted with limited CPU resources, able only to model a laboratory-size chute. The correct CFD modelling of a full-scale stepped spillway would impose CPU and memory requirements that would be economically un-justifiable at present. Beyond the intrinsic numerical errors and bias, the current CFD results have to be upscaled to full-scale spillway with the implicit upscaling errors, already discussed with physical modelling



(a) (b)

(c)

Figure 3. Flow regimes on a stepped spillway model: 1V : 2H(q=26.6°), h=0.10 m(University of Queensland)

Note: (a) Nappe flow(d_c/h=0.133); (b) Transition flow(d_c/h = 0.8); (c) Skimming flow(d_c/h=1.5).

Figure 4. Research student undertaking air-water flow measurements in a 1-m wide stepped spillway flume with a 1V : 1H longitudinal slope and 0.1 m high steps at the University of Queensland

3 Advancement in Stepped Spillway Hydraulics

3.1 Present advances

Laboratory measurements of air-water flows in a stepped chute are not trivial (Ruff and Frizell 1994, Matos 1999), but some advances in metrology combined with advanced post-processing and analyses may provide some in-depth characterisation of the turbulent aerated flows, in large-size facilities under controlled conditions. In self-aerated chute flows, the void fraction C ranges from very low values next to the invert to 100% in the atmosphere, with the mass and momentum fluxes typically conserved in the air-water column within $0<C<0.95$ (Cain and Wood 1981, Wood 1985). In this gas-liquid region ($C<0.95$), the high-velocity self-aerated flow motion is a quasi-homogenous mixture and the two phases, i.e. air and water, travel at identical speed with negligible slip (Rao and Kobus 1974, Chanson 1997). In the air-water flow, the fine characterisation of the turbulent gas-liquid flow necessitates a large number of parameters, including the void fraction, bubble count rate, bubble and drop size distributions, and flow fragmentation properties (Chanson 2013a). Some dedicated instruments were developed, especially the phase-detection needle probes, and more recently the application of the optical flow (OF) technique. The needle probes are designed to pierce the bubble and droplet interfaces, and they are well-suited to track air-water interfaces (Fig. 5). Figure 5 present high-shutter speed photographs of interactions between dual-tip phase-detection needle probes and air-water interface. Although developed in the early 1960s (Neal and Bankoff 1963, 1965), the applications of the needle probe system have drastically expanded over the last two decades, with the successful development of novel advanced signal processing and analysis techniques (Table 2). Further developments might include unbiased signal processing based upon the entire signal processing, as attempted in Zhang and Chanson (2019).

The optical flow (OF) is non-intrusive imaging technique, developed as a set of tools detecting the flow motion between consecutive frames. The OF technique was recently applied to self-aerated stepped spillway flows (Bung and Valero 2016). Sideview OF data were presented, showing great details on the cavity recirculation motion (Bung and Valero 2016, Zhang and Chanson 2018). But some detailed comparison with phase-detection probe data indicated that (a) the OF velocity data underestimated the centreline velocities by 10% to 30%, mostly as a result of sidewall effects, and (b) the OF outputs were meaningless in the upper air-water column, i.e. $C>0.3$ to 0.5 (Zhang and Chanson 2018, Arosquipa Nina et al. 2021). Recently, some top view OF velocity data were also extracted (Arosquipa Nina et al. 2021). Newer developments are underway.

In-depth discussions on the various air-water flow signal post-processing are listed in Table 2. Table 2summarises the key advancements in air-water flow signal analyses at the University of Queensland (2000—2021). The list focuses on a number of novel signal analyses for self-aerated air-water measurements in stepped chute flows, beyond the basic processing of void fraction and interfacial velocity in steady air-water flows (Jones and Delhaye 1976, Cartellier and Achard 1991).

All in all, some fairly major advances have been achieved during the last two decades with respect to detailed physical modelling of two-phase air-water flow in stepped channels. The combination of large-size facilities (Table 1) and complementary advanced instrumentation and signal processing (Table 2) can deliver a fine characterisation of the gas-liquid motion and internal structure down to the sub-millimetric scales.

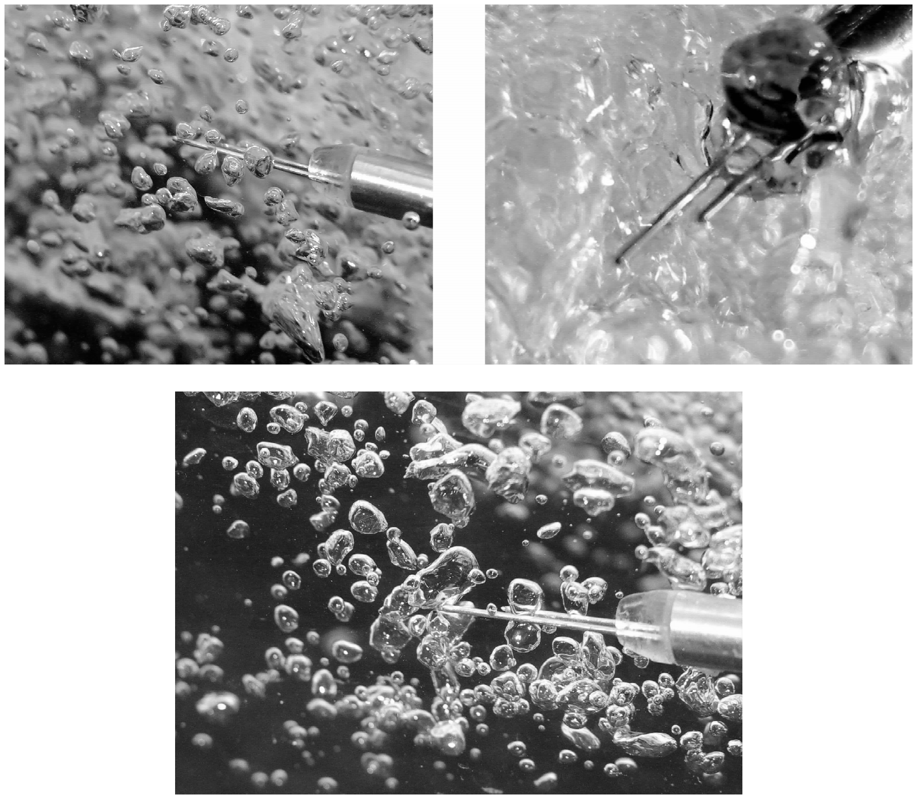


Figure 5. Dual-tip phase-detection probes(DT-PDPs) piercing air-water interface in self-aerated flows-Probe systems designed and manufactured at the University of Queensland

Table 2. Advances in air-water flow signal processing and analyses with a focus on novel signal analyses in self-aerated stepped spillway flows developed at the University of Queensland(2000—2021)

Signal analysis	Outputs	Instrumentation	Reference(s)
Individual bubble detection technique	V, Tu	DT-PDP	Chanson(2005), Wang & Chanson(2015)
Interfacial turbulence intensity	Tu	DT-PDP	Chanson & Toombes(2002, 2003)
1D bubble clustering	N_c, Nb bubbles per cluster, …	ST-PDP	Chanson & Toombes (2002), Chanson(2002)
Relationship between bubble count rate and void fraction	$F/F_{max} = f(C)$	ST-PDP	Toombes (2002), Toombes & Chanson(2008)
Spectral analyses		ST-PDP	Chanson & Gonzalez (2004), Zhang & Chanson(2019)
Integral turbulent time & length scales	T_{xx}, T_{xy}, L_{xy}, L_t, T_t	PDPA	Chanson & Carosi(2007a)
Inter-particle arrival time		ST-PDP	Chanson & Carosi(2007a)
2D bubble clustering	N_c, Nb bubbles per cluster, …	PDPA	Sun & Chanson(2013)
Triple decomposition	C, F, T_{xx}, V, Tu	ST-PDP & DT-PDP	Felder & Chanson(2014)

(To be continued)

(Continue)

Signal analysis	Outputs	Instrumentation	Reference(s)
Total pressure & water turbulence intensity	P_t, Tu_p	M-TPP & ST-PDP	Zhang et al. (2016)
Optical flow(OF)	Turbulent velocity field	UHSC	Zhang & Chanson(2017, 2018)[1]
	Surface velocity field	UHSC & HD-VC	Arosquipa Nina et al. (2021), Chanson(2021)
Adaptive correlation technique	V	DT-PDP	Kramer et al. (2019)
Single-bubble event detection technique	V, Tu	DT-PDP	Shi et al. (2020)

Notes: DT-PDP: dual-tip phase-detection probe; M-TPP: miniature total pressure probe; PDPA: phase-detection probe array; ST-PDP: single-tip phase-detection probe; UHSC: ultra-high-speed camera; HD-VC: high-definition video camera.

[1] the seminal work by Bung and Valero(2016) must be acknowledged.

3.2 The near-future: hybrid modelling(Mark Ⅰ)

In hydraulic engineering, the term "hybridmodelling" is commonly used to design an integrated modelling technique combining physical modelling and computational fluid dynamics(CFD) modelling. The approach has been successfully applied to several hydraulic engineering projects, including box culvert hydrodynamics, unsteady breaking bores, and non-aerated skimming flows on stepped spillways(Meireles et al. 2014, Lopez et al. 2017).

More recently, some fascinating hybridmodelling results were achieved in the non-aerated skimming flow on a stepped spillway(Toro et al. 2016, 2017, Zabaleta et al. 2020). Fig. 6 illustrates an example. The three-dimensional CFD modelling used between 5.4×10^6 and 8.85×10^6 elements, with length about 0.024 to 0.02 times the step height. The results focused on the vorticity patches shed by the stepped cavities until they interacted with the free-surface and "break". The instantaneous vorticity field showed the formation of complex turbulent structures which detached from the stepped invert and were convected in the water column, ultimately interacting with the surface(Toro et al, 2017).

On another hand, detailed 3D CFD modelling are not yet as successful in the air-water skimming flow region downstream of the inception point of free-surface aeration. Current CFD models are not able to reproduce qualitatively and quantitatively the violent air-water ejections, re-attachment and air engulfment observed in prototype stepped spillways(Chanson 2013b, 2021). The modelling of the strong free-surface turbulence is extremely difficult and has to be resolved at the required level of details for further progresses, in the author's opinion.

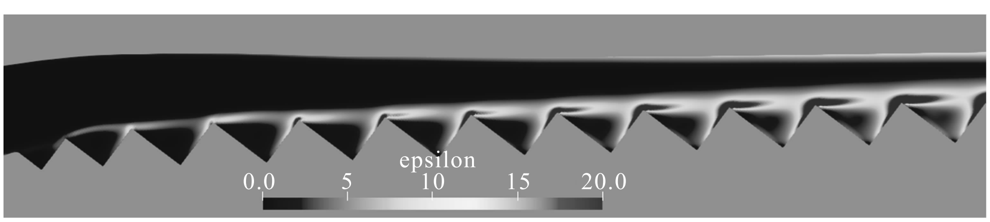


Figure 6. Computational Fluid Dynamics(CFD) modelling of the non-aerated flow region of skimming flow on a stepped chute(q = 51.3°, h = 0.05 m, d_c/h = 2.14): field of dissipation rate of turbulent kinetic energy (TKE)(in m^2/s^3) by Toro et al. (2016) with flow direction from left to right(Courtesy of Prof. F. Bombardelli)

3.3 The near-future: hybrid modelling(Mark Ⅱ)

A different form of modelling may combine laboratory experiments and field observations (Fig. 7). Namely, the approach is based upon some complementary observations with stepped configurations that are geometrically scaled based upon a Froude similarity. Fig. 6 illustrates a recent application, combining optical observations in a prototype stepped spillway and imaging measurements in a relatively large-size laboratory facility. The left side of Fig. 7 presents the field observations. The right side shows some laboratory results. The middle(bottom) graph documents a comparison in terms of the streamwise surface velocity in the non-aerated flow region; the graph shows some good agreement between field observations(thick lines), laboratory observations(cross symbols) and ideal fluid flow theory (tick red dashed line). In practice, the most difficult component is the field observations. In that application(Fig. 7), the author documented several major flood events between 2013 and 2021 at the same facility(Chanson 2021).

The use of optical techniques in prototype spillways is still in the very early stages. Both LSPIV and OF techniques may provide some valuable information on the velocity field(Hauert A, 2021, *Pers. Comm.*, Chanson 2021). To date, the various experiments showed a number of non-trivial challenges. Any imaging technique relies upon physical and optical access, adequate atmospheric and light conditions, experienced operators, and high-resolution high-speed camera equipment. The adequacy of all these conditions is most challenging during a major flood event, particularly during natural disaster situations.

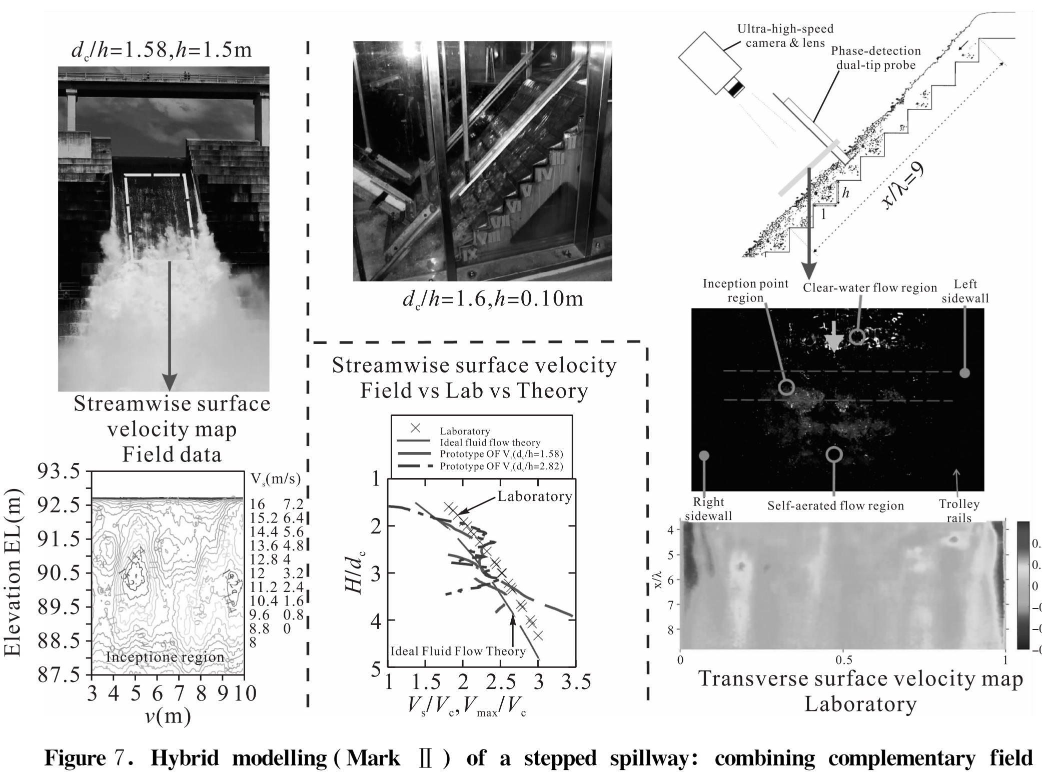


Figure 7. Hybrid modelling (Mark Ⅱ) of a stepped spillway: combining complementary field and laboratory observations-Left: time-averaged streamwise surface velocity map; Middle(bottom): dimensionless comparison of streamwise surface velocity on the channel centreline in the non-aerated flow region, between Prandtl-Pitot tube laboratory data, field OF observations and ideal fluid flow theory; Right: time-averaged transverse surface velocity map in laboratory(Data: Arosquipa Nina et al. 2021, Chanson 2021)

4 Conclusions

The stepped spillway design is well-suited to the stability of gravity dams, while its simplicity of shape and energy dissipation potential are conducive to cost-effective spillway systems, in particular in confined environments. The steps increase significantly the rate of energy dissipation taking place on the steep chute, thus reducing the size of the required downstream stilling structure(s) and the risk of scour. However, hydraulic engineers must analyse carefully the hydraulic operation of stepped spillways and the design is not trivial. The estimation of energy dissipation performances relies heavily upon an accurate prediction of the hydrodynamic properties, including strong turbulence and intense free-surface aeration taking place above the steps. Both strong turbulence and self-aeration are two physical processes always observed in prototype stepped spillways. The hydraulic challenges are amplified to a number of various possible flow regimes, with markedly different flow patterns and hydrodynamic properties.

The hydraulic modelling of stepped spillways may be undertaken physically and/or numerically. Both approaches have their own limitations, discussed above (section 2.2). Laboratory experiments must be conducted in large-size facilities, with multiphase-flow instrumentation. CFD numerical modelling requires some detailed validation, although current practice does not allow a full-scale modelling. All in all, the limitations and costs of hydraulic modelling should not be under-estimated, nor the demands in human resources, i.e. engineers and researchers with a high level of expertise in hydraulic engineering. Recent developments encompass some large-size physical modelling with advanced complementary metrologies, as well some hybrid modelling. Two types of hybrid modelling, Mark I and Mark II, have the potential to deliver a rational, science-based framework of accurate energy dissipation predictions on stepped spillways, and in turn robust and economically-viable spillway designs, to provide our society with reliable flood protection. Any future research on the topic should transcend traditional discipline boundaries by exploiting knowledge derived from state-of-the-art hydraulic modelling and instrumentation techniques for assessing the performances of full-scale prototype structures.

Acknowledgements

The author wishes to acknowledge the exchanges with and contributions of many individuals, including numerous undergraduate research students, his Masters research students (G. Carosi, S. Felder, P. Guenther, D. Wüthrich, Y. Arosquipa Nina), his Ph.D. students (L. Toombes, C. Gonzalez, S. Felder, G. Zhang, R. Shi), and many research collaborators and friends (F. Bombardelli, D. Bung, J. Matos, I. Ohtsu, M. Takahashi, D. Valero, D. Wüthrich, Y. Yasuda). The financial support of the School of Civil Engineering at the University of Queensland (Australia) is acknowledged.

References

[1] AIAA. Editorialpolicy statement on numerical accuracy and experimental uncertainty[J]. AIAA Journal, 1994, 32 (1): 3-3.

[2] Arosquipa Nina Y, Shi R, Wuthrich D. Intrusive and non-Intrusive air-water measurements on stepped spillways with inclined steps: a physical study on air entrainment and energy dissipation. Hydraulic Model Report No. CH121/21

[R]. Brisbane: The University of Queensland, 2021.
[3] Biethman B, Ettema R, Thornton C. Air entrained in flow along a steep-stepped spillway: data and insights from a hydraulic model[J]. Journal of Hydraulic Engineering, 2021, 147(5): 05021001.
[4] Boes R M, Hager W H. Two-phase flow characteristics of stepped spillways[J]. Journal of Hydraulic Engineering, 2003, 129(9): 661—670.
[5] Bombardelli F A. Computational multi-phase fluid dynamics to address flows past hydraulic structures [C]. Proceedings of the 4th IAHR International Symposium on Hydraulic Structures, Porto, Portugal. 2012: 9—11.
[6] Brocchini M, Peregrine D H. The dynamics of strong turbulence at free surfaces. Part 1. Description[J]. Journal of Fluid Mechanics, 2001, 449: 225—254.
[7] Bung D B, Valero D. Optical flow estimation in aerated flows[J]. Journal of Hydraulic Research, 2016, 54(5): 575—580.
[8] Cain P, Wood I R. Measurements of self-aerated flow on aspillway[J]. Journal of the Hydraulics Division, 1981, 107(11): 1425—1444.
[9] Cartellier A, Achard J L. Local phase detection probes in fluid/fluid two-phase flows [J]. Review of Scientific Instruments, 1991, 62(2): 279—303.
[10] Chamani M R, Rajaratnam N. Jet flow on stepped spillways[J]. Journal of Hydraulic Engineering, 1994, 120(2): 254—259.
[11] Chanson H. Hydraulics of skimming flows over stepped channels and spillways[J]. Journal of Hydraulic Research, 1994, 32(3): 445—460.
[12] Chanson H. Hydraulic design of stepped cascades, channels, weirs and spillways[M]. Oxford: Pergamon, 1995.
[13] Chanson H. Air bubble entrainment in free-surface turbulent shear flows[M]. London: Academic Press, 1997.
[14] Chanson H. Historical development of stepped cascades for the dissipation of hydraulic energy[J]. Transactions of the Newcomen Society, 2000, 72(2): 295—318.
[15] Chanson H. The hydraulics of stepped chutes and spillways[M]. Lisse: Balkema, 2001.
[16] Chanson H. Air-water flow measurements with intrusive, phase-detection probes: Can we improve their interpretation? [J]. Journal of Hydraulic Engineering, 2002, 128(3): 252—255.
[17] Chanson H. Air-water and momentum exchanges in unsteady surging waters: an experimental study [J]. Experimental Thermal and Fluid Science, 2005, 30(1): 37—47.
[18] Chanson H. Turbulent air-water flows in hydraulic structures: dynamic similarity and scale effects [J]. Environmental fluid mechanics, 2009, 9(2): 125—142.
[19] Chanson H. Hydraulics of aerated flows: qui pro quo? [J]. Journal of Hydraulic Research, 2013, 51(3): 223—243.
[20] Chanson H. Interactions between a developing boundary layer and the free-surface on a stepped spillway: Hinze Dam spillway operation in January 2013[C]. ICMF, 2013.
[21] Chanson H. Energy dissipation in hydraulic structures[M]. Boca Raton: CRC Press, 2015.
[22] Chanson H. Stepped spillway prototype operation, spillway flow and air entrainment: the hinze dam, australia. hydraulic model report No. CH123/21[R]. Brisbane: The University of Queensland, 2021
[23] Chanson H, Bung D, Matos J. Stepped spillways and cascades [M]. Boca Raton: CRC Press, 2015: 45—64.
[24] Chanson H, Carosi G. Turbulent time and length scale measurements in high-velocity open channel flows [J]. Experiments in Fluids, 2007, 42(3): 385—401.
[25] Chanson H, Carosi G. Advanced post-processing and correlation analyses in high-velocity air-water flows [J]. Environmental Fluid Mechanics, 2007, 7(6): 495—508.
[26] Chanson H, Gonzalez C A. Interactions between free-surface, free-stream turbulence and cavity recirculation in open channel flows: measurements and turbulence manipulation [C]. Proceeding of 5th International Conference on Multiphase Flow, ICMF, Yokohama, 2004: 1—14.
[27] Chanson H, Gonzalez C A. Physical modelling and scale effects of air-water flows on stepped spillways[J]. Journal of Zhejiang University-Science A, 2005, 6(3): 243—250.

[28] Chanson H, Leng X, Wang H. Challenging hydraulic structures of the twenty-first century-from bubbles, transient turbulence to fish passage[J]. Journal of Hydraulic Research, 2021, 59(1): 21—35.

[29] Chanson H, Toombes L. Air-water flows down stepped chutes: turbulence and flow structure observations[J]. International Journal of Multiphase Flow, 2002, 28(11): 1737—1761.

[30] Chanson H, Toombes L. Strong interactions between free-surface aeration and turbulence in an open channel flow [J]. Experimental Thermal and Fluid Science, 2003, 27(5): 525—535.

[31] Chanson H, Toombes L. Hydraulics of stepped chutes: the transition flow[J]. Journal of Hydraulic Research, 2004, 42(1): 43—54.

[32] Chanson H, Yasuda Y, Ohtsu I. Flow resistance in skimming flows in stepped spillways and its modelling[J]. Canadian Journal of Civil Engineering, 2002, 29(6): 809—819.

[33] Ervine D A, Falvey H T. Behaviour of turbulent water jets in the atmosphere and in plunge pools[J]. Proceedings of the Institution of Civil engineers, 1987, 83(1): 295—314.

[34] Felder S, Chanson H. Turbulence, dynamic similarity and scale effects in high-velocity free-surface flows above a stepped chute[J]. Experiments in Fluids, 2009, 47(1): 1—18.

[35] Felder S, Chanson H. Triple decomposition technique in air-water flows: application to instationary flows on a stepped spillway[J]. International Journal of Multiphase Flow, 2014, 58: 139—153.

[36] Horner M W. An analysis of flow on cascades of steps[D]. Birmingham: University of Birmingham, 1969.

[37] Rodier J A, Roche M. World catalogue of maximum observed floods[J]. IAHS-AISH publication, 1984(143).

[38] JonesJr O C, Delhaye J M. Transient and statistical measurement techniques for two-phase flows: a critical review [J]. International Journal of Multiphase Flow, 1976, 3(2): 89—116.

[39] Kramer M, Valero D, Chanson H. Towards reliable turbulence estimations with phase-detection probes: an adaptive window cross-correlationtechnique[J]. Experiments in Fluids, 2019, 60(1): 1—6.

[40] Lopes P, Leandro J, Carvalho R F. Alternating skimming flow over a stepped spillway[J]. Environmental Fluid Mechanics, 2017, 17(2): 303—322.

[41] Lubin P. Wave breaking and air entrainment[J]. Advanced Numerical Modelling of Wave Structure Interactions, 2021: 69—85.

[42] Matos J. Emulsionamento de ar e dissipação de energia do escoamento em descarregadores em degraus. (Air entrainment and energy dissipation in flow over stepped spillways.)[D]. Lisbon: Instituto Superior Técnico, 1999.

[43] Matos J, Meireles I. Hydraulics of stepped weirs and dam spillways: engineering challenges, labyrinths of research [C]//11th National Conference on Hydraulics in Civil Engineering & 5th International Symposium on Hydraulic Structures: Hydraulic Structures and Society-Engineering Challenges and Extremes. Engineers Australia, 2014: 330.

[44] Meireles I C, Bombardelli F A, Matos J. Air entrainment onset in skimming flows on steep stepped spillways: an analysis[J]. Journal of Hydraulic Research, 2014, 52(3): 375—385.

[45] Neal L G, Bankoff S G. A high resolution resistivity probe for determination of local void properties in gas-liquid flow[J]. AIChE Journal, 1963, 9(4): 490—494.

[46] Neal L G, Bankoff S G. Local parameters in cocurrent mercury-nitrogen flow: Parts Ⅰ and Ⅱ[J]. AIChE Journal, 1965, 11(4): 624—635.

[47] Novák P, Čabelka J. Models in hydraulic engineering: physical principles and design applications[M]. Pitman Publishing, 1981.

[48] Novak P, Moffat, A I B, Nalluri C. Hydraulic structures[M]. London: E & FN Spon, 1996.

[49] Peyras L, Royet P, Degoutte G. Flow and energy dissipation over stepped gabion weirs[J]. Journal of hydraulic Engineering, 1992, 118(5): 707—717.

[50] Prosperetti A, Tryggvason G. Computational methods for multiphase flows[M]. Cambridge: Cambridge University Press, 2009.

[51] Rajaratnam N. Skimming flow in stepped spillways[J]. Journal of Hydraulic Engineering, 1990, 116(4): 587—591.

[52] Rao N S L, Kobus H, Barczewski B. Characteristics of self-aerated free-surface flows (Water and waste water current research and practice)[M]. Berlin, Bielefeld, Mu̍nchen: E. Schmidt, 1975.
[53] Roache P J. Verification of codes and calculations[J]. AIAA journal, 1998, 36(5): 696-702.
[54] Rodi W. Turbulence modeling and simulation in hydraulics: A historical review [J]. Journal of Hydraulic Engineering, 2017, 143(5): 03117001.
[55] Rodi W, Constantinescu G, Stoesser T. Large-eddy simulation in hydraulics[M]. Leiden: Crc Press, 2013.
[56] Rojas R, Feyen L, Watkiss P. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation[J]. Global Environmental Change, 2013, 23(6): 1737-1751.
[57] Ruff J F, Frizell K H. Air concentration measurements in highly-turbulent flow on a steeply-sloping chute[C]// Hydraulic Engineering. ASCE, 1994: 999-1003.
[58] Shi R, Wüthrich D, Chanson H. Introducing a single bubble event detection technique for air-water interfacial velocity measurements in unsteady turbulent bore[C]. Proceedings of 22nd Australasian Fluid Mechanics Conference AFMC20202020, Brisbane: The University of Queensland, 2020: 20-24.
[59] Sorensen R M. Stepped spillway hydraulic model investigation[J]. Journal of hydraulic Engineering, 1985, 111 (12): 1461-1472.
[60] Sun S, Chanson H. Characteristics of clustered particles in skimming flows on a stepped spillway [J]. Environmental fluid mechanics, 2013, 13(1): 73-87.
[61] Tombes L. Experimental study of air-water flow properties on low-gradient stepped cascades[D]. Brisbane: The University of Queensland, 2002.
[62] Toombes L, Chanson H. Surface waves and roughness in self-aerated supercritical flow[J]. Environmental Fluid Mechanics, 2007, 7(3): 259-270.
[63] Toombes L, Chanson H. Interfacial aeration and bubble count rate distributions in a supercritical flow past a backward-facing step[J]. International Journal of Multiphase Flow, 2008, 34(5): 427-436.
[64] Toro J P, Bombardelli F A, Paik J. Characterization of turbulence statistics on the non-aerated skimming flow over stepped spillways: a numerical study[J]. Environmental Fluid Mechanics, 2016, 16(6): 1195-1221.
[65] Toro J P, Bombardelli F A, Paik J. Detached eddy simulation of the nonaerated skimming flow over a stepped spillway[J]. Journal of Hydraulic Engineering, 2017, 143(9): 04017032.
[66] UNDRR. Global assessment report on disaster risk reduction 2019[R]. Geneva: United Nations Office for Disaster Risk Reduction, 2019.
[67] USBR. US Department of the interior, bureau of reclamation, Denver CO, USA, 1st edition, 3rd printing[J]. Design of Small Dams, 1965.
[68] Vischer D, Hager W H. IAHR Hydraulic Structures Design Manual No. 9: Hydraulic Design Considerations[J]. Energy Dissipators, 1995.
[69] Wang H, Chanson H. Experimental study of turbulent fluctuations in hydraulic jumps[J]. Journal of Hydraulic Engineering, 2015, 141(7): 04015010.
[70] Wegmann E. The design and construction of dams[M]. New York: John Wiley & Sons, 1911.
[71] Wood I R. Air water flows[C]. Proceding of 21st IAHR Congress, Melbourne, Australia, Keynote address, 1985: 18-29.
[72] Wüthrich D, Chanson H. Hydraulics, air entrainment, and energy dissipation on a Gabion stepped weir[J]. Journal of Hydraulic Engineering, 2014, 140(9): 04014046.
[73] Zabaleta F, Bombardelli F A, Toro J P. Towards an understanding of the mechanisms leading to air entrainment in the skimming flow over stepped spillways[J]. Environmental Fluid Mechanics, 2020, 20(2): 375-392.
[74] Zhang G, Chanson H. Application of local optical flow methods to high-velocity air-water flows: validation and application to skimming flows on stepped chutes. hydraulic model report No. CH105/17 [R]. Brisbane: The University of Queensland, 2017.
[75] Zhang G, Chanson H. Application of local optical flow methods to high-velocity free-surface flows: Validation and

application to stepped chutes[J]. Experimental Thermal and Fluid Science, 2018, 90: 186−199.

[76] Zhang G, Chanson H. On void fraction and flow fragmentation in two-phase gas-liquid free-surface flows[J]. Mechanics Research Communications, 2019, 96: 24−28.

[77] Zhang G, Chanson H, Wang H. Total pressure fluctuations and two-phase flow turbulence in self-aerated stepped chute flows[J]. Flow Measurement and Instrumentation, 2016, 51: 8−20.