Springer

Available online at https://link.springer.com/journal/42241
http://www.jhydrodynamics.com
Journal of Hydrodynamics, 2022, 34(1): 52-62
https://doi.org/10.1007/s42241-022-0005-8

Energy dissipation on stepped spillways and hydraulic challenges–Prototype and laboratory experiences

Hubert Chanson*
School of Civil Engineering, The University of Queensland, Brisbane, Australia

(Received August 4, 2021, Revised September 22, 2021, Accepted September 23, 2021, Published online February 25, 2022)

Abstract: Stepped cascades, chutes and spillways have been in use for more than three millennia. With the introduction of new construction materials and techniques, the staircase chute design has regained some interest within the last forty years. The stepped invert increases significantly the energy dissipation occurring above the steep chute and reduces the size of the required downstream stilling structure. The application of stepped chutes further encompasses in-stream re-aeration and water treatment plant cascades, to enhance the air-water transfer of atmospheric gases and of volatile organic components. However, the engineering design of stepped spillways is not simple because of the hydrodynamic challenges, with several markedly different flow regimes, some complicated two-phase air-water fluid dynamics and massive rate of energy dissipation above the stepped chute. Simply, the technical challenges in the hydraulic design of stepped spillways are massive. This review paper examines the hydraulic characteristics of stepped chute flows and develops a reflection on nearly three decades of active hydraulic research, including recent field measurements during major flood events. The author aims to share his passion for the complicated hydraulic engineering, as well as some advice for engineering professionals and researchers.

Key words: Stepped spillways, hydraulic modeling, field measurements, energy dissipation and design, multiphase air-water flows

Introduction

Many parts on our planet are subjected to hydrological extremes, with spatial and temporal variability and uncertainty. Flooding is the most frequently occurring natural disaster in the world and has been increasing during the last two decades at an alarming rate[1]. It is expected that extreme flooding will occur even more frequently as a result of climate change[2]. In addition to the expected increase in the magnitude and frequency of future extreme rainfall and runoff events, the world's population is predicted to increase from the current level of 7.7×10^9 to 10.2×10^9 in 2060. Intense rainfall events will convert into large floods as the surface runoff converges into valleys and streams. In the face of pressures such as population growth, catchment development and climate change, catastrophic failures of critical infrastructure with the associated losses of life and exorbitant aftermath damage costs, will constitute an increasing threat to our society.

In spite of the continuous hydrological cycle of water, the rainfall pattern on Earth is not uniform. The catalogue of the world's maximum floods highlighted some astonishing record flow rates[3]. In contrast, many regions have experienced recurrent long droughts for the last three centuries, e.g., Africa, Americas, Australia and Central Asia. Man-made reservoirs are one of the most efficient means to deliver both flood protection and long-term reliable water reserves. During a major flood event, the dam must be equipped with a spillway system to discharge safely the excess flood waters[4-5]. In terms of hydraulic design, the purpose of a spillway is two-fold: (1) the safe conveyance of floodwaters and (2) the safe dissipation of the kinetic energy, before the floodwaters rejoin the naturel river channel. The dissipation of the kinetic energy takes place down the steep chute and at the downstream end of the spillway system. The amount of energy dissipation can be truly astonishing[6]. In terms of design, the energy dissipation may take place at the downstream end of the spillway, in a hydraulic jump stilling structure, with a ski jump and a plunge pool, or using an impact dissipator, as well as down the spillway chute with the installation of macro-roughness[7-8]. With modern spillway designs, the simplest form of macro-roughness is a staircase invert, that can be easily accommodated during construction[9-10] (Fig. 1).

Biography: Hubert Chanson (1961-), Ph. D., Professor
Corresponding author: Hubert Chanson,
E-mail: h.chanson@uq.edu.au

Fig. 1 (Color online) Stepped spillways. (a) Gold Creek Dam (Australia, 1890) on 23 February 2015, (b) Riou Dam (France, 1990) in February 2004, (c) Hinze Dam Stage 3 (Australia, 2011) on 26 September 2018, (d) Mujib Dam (Jordan, 2004) in September 2012 (Courtesy Philipp Günther)

1. Stepped spillways: design and hydraulics

1.1 *Presentation*

Stepped cascades, chutes and spillways have been in use for several millennia[11]. During the 19th and early 20th centuries, a substantial amount of dams were designed with a "staircase wastewaterway", i.e., a stepped spillway (Fig. 1(a))[12-13]. The development of the hydraulic jump stilling basin at the toe of smooth spillways led to a lesser interest for the stepped chutes. In the last 40 years, some advancement in construction technology, e.g., roller compacted concrete, and increased geographical constraints of several dam sites, have brought back a strong interest for the stepped spillway design (Figs. 1(b)-1(d), 2). During overflows, the staircase invert acts as uniformly-distributed macro-roughness, that increase substantially the energy dissipation along the steep chute, in turn reducing the size and cost of the downstream stilling system[14-15] and enabling a more compact spillway structure.

Fig. 2 (Color online) Very strong turbulence and intense self-aeration on a stepped spillway. Paradise Dam stepped spillway operation on 5 March 2013 for $Q = 2\,320\ \mathrm{m^3/s}$, $d_c / h = 2.85$, $h = 0.62$ m, skimming flow regime (shutter speed: 1/2000 s)

Some key features of the stepped spillway design include the wide spread of projects in all continents except Antarctica, the broad diversity of applications, the wide range of construction materials and design flow rates. The stepped design has been successfully used for re-aeration cascades, sabo check dams, embankment overtopping protection systems, storm waterways and urban systems, low-head weirs, large concrete dam spillways. The step construction may be undertaken with gabions and Reno mattresses, timber cribs, precast concrete blocks, roller compacted concrete and conventional concrete. The design unit discharges range from less than 0.1 m^2/s to more than 100 m^2/s. In each project, the stepped chute operation is characterised by some complicated hydrodynamics during design and non-design operations, that requires a high level of hydraulic expertise during the design stages.

In the next paragraphs, the author will share some thoughts in the challenges associated with the fluid dynamics and hydraulic design of stepped spillways, based upon his 30 years of experiences on the topic. These add to an earlier relevant keynote paper[16], while a few seminal papers[17-19]are further pertinent to the discussion. 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[9, 10, 8].

1.2 *Stepped spillway hydraulics and its challenges*

The fluid dynamics of stepped chute flows is a complicated topic[20, 15, 21-22]. The challenges encompass (1) the very strong turbulence and intense self aeration, (2) the markedly different flow regimes that may occur on a given stepped geometry, depending upon the unit discharge and step geometry and (3) the intrinsic limitations of both physical modelling and computational techniques.

First, the stepped invert profile generates some intense turbulent dissipation during the operation, associated with a significant dissipation in kinetic energy, as well as strong self-aeration through the free-surface (Fig. 2)[23, 9, 24-26]. The steps induce some flow separation in the wake of each step's outer edge, which leads to the development of strong cavity recirculation. At large unit discharges, the recirculation motion is maintained through some irregular transfer of mass and momentum between the mainstream and the step cavity region, i.e. with cavity ejection and replenishment occurring relatively rapidly in a pseudo-periodic fashion[27-28]. The large-scale turbulence is shed from the triangular cavities into the main flow, and ultimately interacts with the free surface[29-31]. Very large turbulence levels are observed throughout the entire air-water column, including in the vicinity of the free-surface. The very strong free-surface turbulence generates an uncontrolled air-water free-surface exchange, since neither gravity nor surface tension can maintain the water surface cohesion[32-34]. Visually, large amounts of water ejections and air entrapment are seen, with complicated air-water structure ejections, and re-attachments further downstream, while the fluid ejections are complemented with strong air engulfment (Figs. 1(a), 2 and 3). The processes are violent, with the “eruptions”of air-water masses believed to be induced by the collision of tilted powerful large-scale streamwise vortices with the upper surface[28, 30-31]. During prototype operations, the upper free-surface may further experience “surface waves”, e.g., illustrated at Chinchilla weir (Australia)

Table 1 Stepped spillway research at the University of Queensland: Characteristics of main physical facilities (1995-2021)

θ /°	h /m	B /m	q /$m^2 \cdot s^{-1}$	Step configuration	Others
2.6	0.1430	0.250	0.0700-0.1400	Flat horizontal	Single drop
3.4	0.0715, 0.1430	0.500	0.0380-0.1630	Flat horizontal	-
3.4	0.0715, 0.1430	0.500	0-0.0750	Flat horizontal	Dam break wave
15.9	0.0500, 0.1000	1.000	0.0200-0.2600	Flat horizontal	-
21.8	0.0500, 0.1000	1.000	0.0080-0.1900	Flat horizontal	-
21.8	0.1000	1.000	0.1000-0.2190	Triangular vanes	-
21.8	0.1000	1.000	0.0100-0.2410	Rough steps	-
26.6	0.1000	0.520	0.0050-0.2410	Flat horizontal	-
26.6	0.1000	0.520	0.0030-0.2820	Pooled steps	2-D, 3-D
26.6	0.1000	0.520	0.0380-0.2800	Gabion steps	-
45.0	0.1000	0.985	0.0010-0.3000	Flat horizontal	-
45.0	0.1000	0.985	0.0830-0.2160	Trapezoidal cavities	-
45.0	0.1000	0.985	0.0008-0.2800	Inclined steps	-
51.3	1.5000	12.250	5.8000-27.3000	Flat horizontal	Prototype

Notes: θ is the longitudinal chute slope, h is the vertical step height, B is the chute width and q is the unit discharge.

and Three-Gorges Project (China)[35].

Second, a stepped spillway flow may be one of several markedly different flow regimes, for a fixed stepped geometry, depending upon the unit discharge. Considering the simplest step geometry, i.e., flat horizontal impervious steps in a rectangular prismatic chute, the flow is either a jet flow at small unit discharges (Figs. 1(a), 3(a)), a transition flow for a range of intermediate discharges (Fig. 3(b)) or a skimming flow at large unit discharges (Figs. 2, 3(c)). The jet flow regime, also called nappe flow, has been commonly used in older stepped spillway designs completed during the 18th to early 20th centuries, and it corresponds to relatively small unit discharges[20, 36]. The transition flow regime is characterised by large hydrodynamic instabilities and strongly chaotic flow conditions, which should be avoided during overflows, unless at small flow rates[37]. The skimming flow is typically observed on modern concrete gravity dam stepped spillways[14, 22, 38]. Each flow regime has very distinct flow features (Fig. 3). Figure 3 shows the three distinctly different flow regimes in a prototype stepped spillway. More complex step configurations might experience more than three flow regimes, e.g., four flow regimes may be seen on gabion stepped chutes[39], stationary and non-stationary regimes were reported on pooled step spillways[40].

Third, the hydraulic modelling of stepped spillways is difficult. Traditionally, physical laboratory experiments were designed and conducted based upon a Froude similitude[41-42, 14]. The upscaling of laboratory data may be affected by major scaling effects, with the use of small-size laboratory facilities. Recent studies demonstrated that any laboratory experiments must be conducted at large Reynolds numbers, i.e., $Re > 1.0 \times 10^5$ - 5.0×10^5, to minimise potential scaling issues[43-44], although scale effects cannot be totally eliminated unless working at 1:1, i.e., at full scale. As a result, the pre-requisite usage of large-size laboratory facilities is absolutely necessary, with required flow conditions implying relatively large discharges which may be economically expensive (Fig. 4). Figure 4 shows an example of a large-size facility operating at a large Reynolds number: $Re = 8.8 \times 10^5$. The flow turbulence and self-aeration in these large physical facilities further mean the required usage of multiphase flow metrologies, with relatively expensive fine instrumentation, operated by expert experimentalists. The implications in terms human resources should not be under-stated nor its cost under-estimated. Indeed, civil engineering undergraduate and postgraduate students are not taught about multiphase fluid dynamics at universities. In his own university, the author would educate and train any new research student for 2-6 months, before he/she can conduct reliable air-water flow measurements of acceptable quality.

Fourth, for the last few decades, another type of hydraulic modelling is the computational fluid dynamics (CFD) modelling. The CFD modelling is based upon the numerical integration of the Navier-Stokes equations[45-46]. In the last two to three decades, several studies presented some multiphase-dedicated

(a) (b) (c)

Fig. 3 (Color online) Flow regimes on a prototype stepped spillway: Hinze Dam Stage 3 (Australia), $\theta = 51.3°$, $h = 1.50$ m. (a) Nappe flow $(d_c / h = 0.080)$ on 2 May 2021, (b) Transition flow $(d_c / h = 0.045)$ on 3 May 2015, (c) Skimming flow $(d_c / h = 1.360)$ on 23 March 2021

CFD models[47-48]. The equations for two-phase flows may be applied to and stepped spillway flows[17, 49]. But, not all the results are equal, nor all the outputs are correct. Very often, the CFD modelling is not validated or improperly validated, leading to numerous outputs of physically meaningless results. As a journal editor and senior expert reviewer, the author has read too many erroneous CFD reports and manuscripts with meaningless and useless data outputs. While the ASME and AIAA presented clear recommendations and guidelines for CFD verification and validation[50-52], the advice is rarely applied rigorously in hydraulic engineering including in stepped spillway hydraulics. Another issue is a lack of detailed laboratory data sets of high quality and of field observations, which constitute pre-requisites for proper CFD validation. This is not trivial not simple. Practically, the laboratory experiments do not always include the required detailed information at all spatio-temporal scales, for adequate CFD model validation. There is no doubt that the potential applications of CFD to stepped spillway hydrodynamics could offer a large interest, once adequately validated, to complement physical observations (see Section 3.2). A major challenge is the limitations in computational resources. To date, all the CFD modelling has been conducted with laboratory-sized domains because of limited CPU resources. 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 acknowledged with physical modelling. Presently, the correct CFD modelling of a full-scale stepped spillway would impose CPU and memory requirements that would be economically unjustifiable at present.

2. Future advances in stepped spillway hydraulics

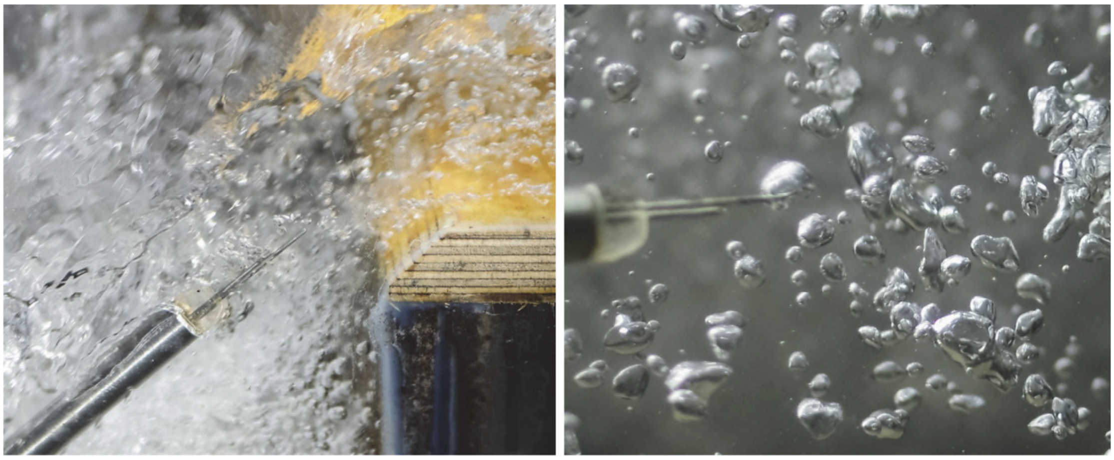
2.1 *Present advances*

Physical measurements of air-water flow properties in a stepped channel are difficult because of the strong surface aeration and turbulence[53, 38, 24]. Recent advancements in the metrology, together with novel advanced signal processing and data analyses, pave the way for an accurate estimate of the rate of energy dissipation based upon an in-depth characterisation of the gas-liquid turbulent flows down to the sub-millimetric scales, in large-size facilities operating under controlled flow conditions.

In a high-velocity air-water chute flow, the local void fraction C typically ranges from very low values next to the invert up to 100% above the free-surface. Basically, the mass and momentum fluxes are conserved in the air-water column for $0 < C < 0.95$ [54-55]. In this fully-mixed gas-liquid region $(0 < C < 0.95)$, the high-velocity self-aerated flow motion behaves like a quasi-homogenous mix, and the two phases, i.e. air and water, travel at a quasi-identical speed with negligible slip[56-57]. In the multiphase gas-liquid, the fine characterisation of the turbulent flow requires a large number of parameters, including the void fraction, bubble count rate, bubble and drop size distributions, and flow fragmentation properties[58, 18]. 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 phase-detection sensors designed to pierce the bubble and droplet interfaces, that are well-suited to track air-water interfaces (Fig. 5). Figure 5 present high-shutter speed (1/8000 s) photographs of interactions between dual-tip phase-detection needle probes and entrained bubbles in self-aerated flows. First developed in the early 1960s[59-60], the applications of the needle probes have substantially expanded over the last three decades, with the successful development of several novel advanced signal processing and analysis techniques (Table 2). Further relevant developments encompass unbiased signal processing based upon the entire signal processing, as proposed by Zhang and Chanson[61].

Fig. 4 (Color online) 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–Flow conditions: $d_c / h = 1.700$, $Re = 8.8 \times 10^5$

The optical flow (OF) is an imaging technique, detecting the flow motion between consecutive frames. The OF technique was recently applied to self-aerated stepped spillway flows[62]. The sideview OF data



(a) (b)

Fig. 5 (Color online) Dual-tip phase-detection probes (DT-PDPs) piercing air-water interface in self-aerated flows (Shutter speed: 1/8000 s)–Probe systems designed and manufactured at the University of Queensland)–For scale, the outer needle sensor diameter (of the DT-PDP) was 0.8 mm and the needle tubular support (far right) had a 8.0 mm diameter

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	References
Individual bubble detection technique	V, Tu	DT-PDP	Chanson[67], Wang and Chanson[68]
Interfacial turbulence intensity	Tu	DT-PDP	Chanson and Toombes[69, 24]
1-D bubble clustering	N_c, N_b bubbles per cluster, …	ST-PDP	Chanson and Toombes[69], Chanson[70]
Relationship between bubble count rate and void fraction	$F / F_{max} = f(C)$	ST-PDP	Toombes[71], Toombes and Chanson[72]
Spectral analyses	-	ST-PDP	Chanson and Gonzalez[73], Zhang and Chanson[61]
Integral turbulent time and length scales	T_{xx}, T_{xy}, L_{xy}, L_t, T_t	PDPA	Chanson and Carosi[74]
Inter-particle arrival time	-	ST-PDP	Chanson and Carosi[75]
2-D bubble clustering	N_c, N_b bubbles per cluster, …	PDPA	Sun and Chanson[76]
Triple decomposition	C, F, T_{xx}, V, Tu	ST-PDP and DT-PDP	Felder and Chanson[40]
Total pressure and water turbulence intensity	P_t, Tu_p	M-TPP and ST-PDP	Zhang et al.[77]
OF	Turbulent velocity field	UHSC	Zhang and Chanson[78, 63] ([1])
OF	Surface velocity field	UHSC and HD-VC	Arosquipa Nina et al.[64], Chanson[31]
Adaptive correlation technique	V	DT-PDP	Kramer et al.[79]
Single-bubble event detection technique	V, Tu	DT-PDP	Shi et al.[80]

Notes: Dual-tip phase-detection probe (DT-PDP), miniature total pressure probe (M-TPP), phase-detection probe array (PDPA), single-tip phase-detection probe (ST-PDP), ultra-high-speed camera (UHSC), high-definition video camera (HD-VC), ([1]): the seminal work by Bung and Valero[62] must be acknowledged.

showed great details on the cavity recirculation motion[62-63]. But a detailed comparison between OF velocity data and dual-tip phase-detection probe velocity data demonstrated that (1) the OF velocity data systematically under-estimated the centreline velocities by 10%-30%, mostly as a result of sidewall effects, (2) the OF velocity results were meaningless in the upper half of the air-water column, i.e., $C > 0.30$ - 0.50 with C the void fraction[63-64]. Very recently, the top view OF velocity data were also extracted, yielding surface velocity and turbulence contour maps[64]. Newer applications are still under development[31].

In-depth reviews on air-water flow signal post-processing developments are listed in Table 2. Table 2 summarises the seminal advances in air-water flow signal analyses at the University of Queensland for the last twenty years. The table lists novel signal processing and analyses for air-water measurements in stepped spillway overflows, beyond the simple well-understood processing of void fraction and interfacial velocity in steady air-water flows[65-66].

All in all, some fairly major advances have been achieved during the last two decades with respect to detailed physical modelling of self-aerated flows in stepped spillways. The combination of large-size physical facilities (Table 1) and complementary advanced metrologies (Table 2) deliver a detailed characterisation of the gas-liquid turbulent flow motion as well as its internal structure down to the 0.1 mm scales.

2.2 *The near-future: hybrid modelling (Mark I)*

In hydraulic engineering, the expression "hybrid modelling" commonly refers to an integrated modelling technique combining physical modelling and numerical models, including CFD modelling. The approach has been successfully used in several hydraulic engineering projects, including box culvert hydrodynamics and unsteady breaking surges. Some preliminary studies in skimming flows on stepped spillways included Meireles et al.[81], Lopez et al.[82].

Recently, some fascinating hybrid modelling outputs were obtained in the non-aerated region of skimming flows on a stepped spillway[49, 83]. Figure 6 illustrates an example of results. The three-dimensional CFD models used between 5.40×10^6, 8.85×10^6 elements, with dimensions about 0.024-0.020 times the vertical step height h. The outputs illustrated the role of vorticity patches shed by the step edges and their initial interaction with the free-surface, leading to surface "breaking". The instantaneous vorticity field data highlighted the formation of complex turbulent structures which detached from the stepped invert and were convected in the water column, until they started to interact with the surface[28-29]. The CFD data presented an astonishing agreement with recent field observations in a large stepped spillway[30-31].

On another hand, detailed 2-D, 3-D 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 eruptions, re-attachment and air engulfment documented in prototype stepped spillways[16, 30-31]. The modelling of such a very strong free-surface turbulence is extremely difficult and beyond the current computational resources. Its resolution requires a higher level of details for further progresses, in the author's opinion.

2.3 *The near-future: hybrid modelling (Mark II)*

An alternate form of hybrid modelling may be based upon a complementary usage of laboratory experiments and field observations (Fig. 7). That is, the approach is based upon some similar observations with stepped spillways that are geometrically scaled based upon an un-distorted Froude similitude. Figure 7 illustrates a very recent project, combining optical observations in a prototype stepped spillway and imaging measurements in a relatively large-size laboratory facility. The (top) left side of Fig. 7 shows the OF surface velocity observations in prototype $(h=1.50\text{ m})$. The right side presents some physical data in laboratory channel in a 1:15 scale model $(h=0.10\text{ m})$. The bottom left graph shows a comparison in terms of the dimensionless streamwise surface velocity in the non-aerated flow region. The graph illustrates a good agreement between ideal fluid flow theory (tick red dashed line), field observations (thick lines), and laboratory observations (cross symbols). Practically, the most difficult component constitutes the field measurements. In the application highlighted in Fig. 7, several major flood events were documented between 2013, 2021 at the same facility[30-31].

The use of optical techniques in prototype spillways is still in some very-early stages. Both LSPIV, OF techniques may provide some invaluable information on the surface velocity field[31]. To date, the few

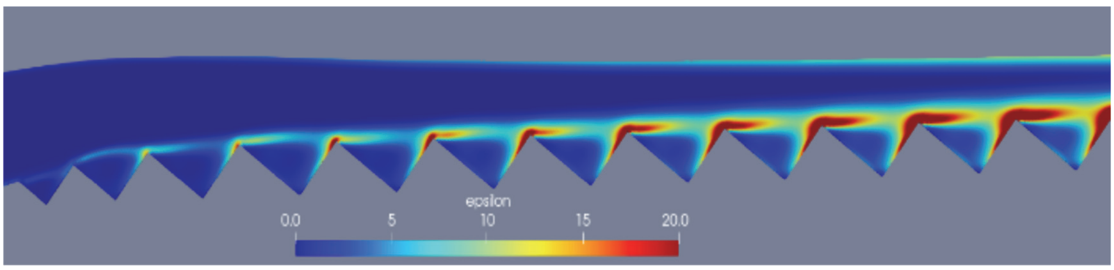


Fig. 6 (Color online) CFD modelling of the non-aerated flow region of skimming flow on a stepped chute ($\theta=51.3°$, $h=0.05\text{ m}$, $d_c/h=2.14$): field of dissipation rate of turbulent kinetic energy (TKE) (in m^2/s^3) by Toro et al.[28] with flow direction from left to right (Courtesy of Prof. F. Bombardelli)

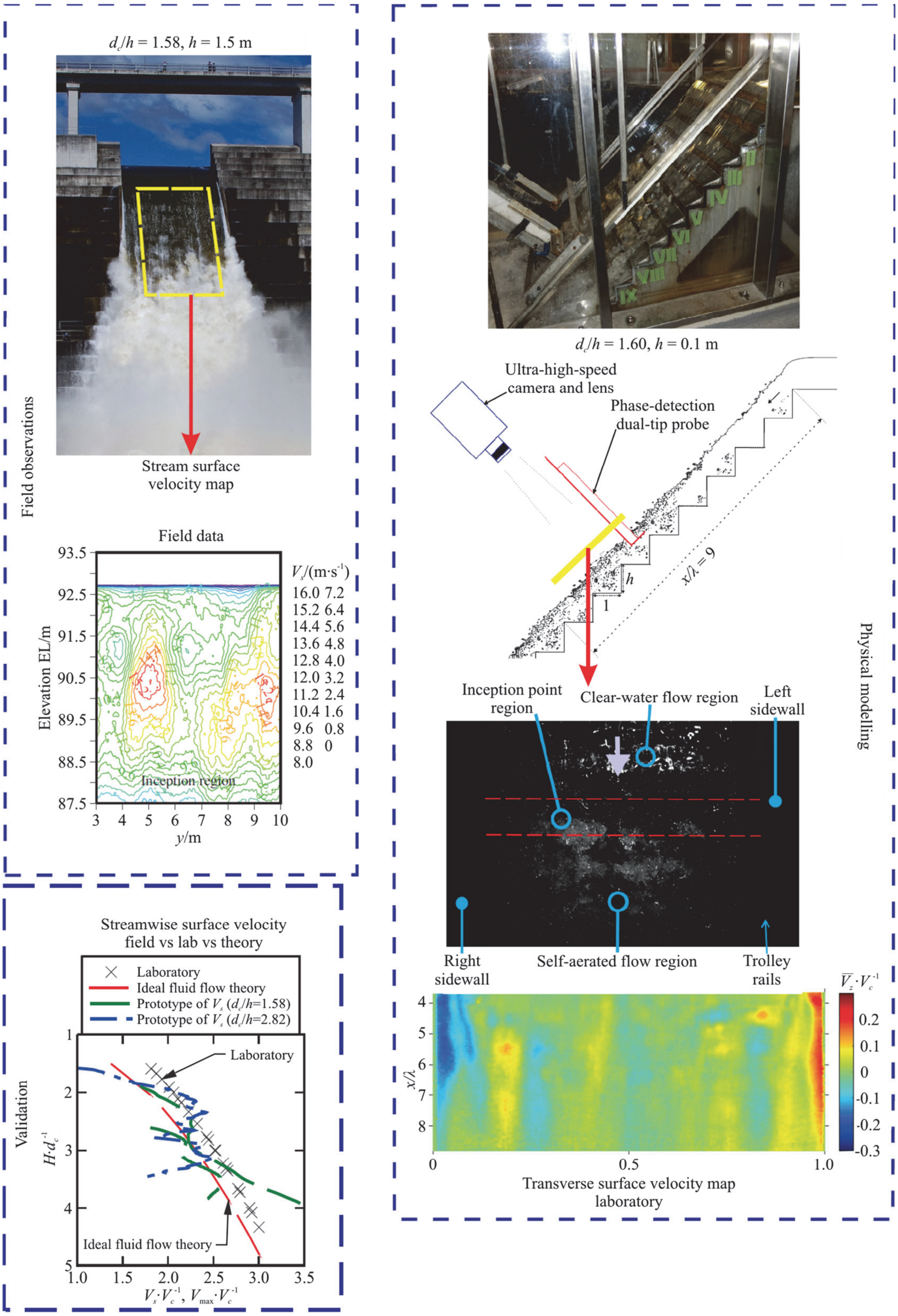


Fig. 7 (Color online) Hydrid modelling Mark II of a steep stepped spillway: combining complementary field and laboratory observations (Data: Arosquipa Nina et al.[50], Chanson[31])–Left: time-averaged streamwise surface velocity map, Middle (bottom): dimensionless comparison of streamwise surface velocity 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

experiments indicated a number of difficult technical challenges. With any imaging technique, the data quality is directly linked to physical and optical access, adequate atmospheric and light conditions, experienced operators, and high-resolution high-speed camera equipment. The combination of all these conditions is most challenging during a major flood event, particularly during natural disaster situations.

3. Concluding comments: Why does it matter?

The stepped spillway design is well-suited to the stability of gravity dams, and the simplicity of shape and energy dissipation potential can deliver cost-effective spillway chutes, especially in confined environments. The steps increase significantly the rate of energy dissipation taking place on the steep chute, in turn reducing the size of the required downstream stilling structures and the risk of scour. In practice, the hydraulic design engineers must estimate carefully the hydraulic properties of stepped spillway overflows during design and non-design flow conditions. The hydraulic design is not trivial. The accurate estimate of energy dissipation performances relies heavily upon a correct prediction of the hydrodynamic properties above the stepped chute, including the very strong turbulence and intense self-aeration taking place above the staircase invert. Both very strong turbulence and free-surface aeration are two violent physical processes always observed in prototype stepped cascades and chutes. The technical challenges are intensified by a number of various possible flow regimes, with markedly different flow patterns and complex hydrodynamic properties.

The hydraulic modelling of stepped spillways may be conducted physically, numerically or both. All the approaches have their intrinsic limitations, discussed above (Section 2.2). Noteworthy, all the methods include a solid physical modelling component. Laboratory experiments must be performed in large-size facilities, with multiphase-flow metrologies, to minimise scaling issues. The CFD numerical modelling demands some detailed and robust validation, although the current deficiencies in computational resources do not allow a full-scale modelling in practice. Recent developments encompass some large-size physical modelling with advanced complementary metrologies, as well some hybrid modelling (Section 3). Two types of hybrid modelling, Mark I, 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. Yet, 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.

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. Wűthrich and Y. Arosquipa Nina), his Ph. D. Candidates (L. Toombes, C. Gonzalez, S. Felder, H. Wang, G. Zhang and R. Shi), and many research collaborators and friends (F. Bombardelli, D. Bung, J. Matos, I. Ohtsu, M. Takahashi, D. Valero, D. Wűthrich and Y. Yasuda). The present manuscript derives from a plenary presentation at the 2nd International Symposium of Water Disaster Mitigation and Water Environment Regulation[84], and the encouragements of Prof. Hang Wang (Sichuan University) are acknowledged. The financial support of the School of Civil Engineering at the University of Queensland (Australia) is acknowledged.

References

[1] UNDRR. Global assessment report on disaster risk reduction [R]. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction, 2019.

[2] 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]. *Glob Environmental Change*, 2003, 23(6): 1737-1751.

[3] IAHS. World catalogue of maximum observed floods [R]. IAHS-AISH Publication No. 143, Wallingford, UK, 1984.

[4] USBR. Design of small dams [R]. 1st Edition, Denver CO, USA: US Department of the Interior, Bureau of Reclamation, 1965.

[5] Novak P., Moffat A. I. B., Nalluri C. et al. Hydraulic structures [M]. London, UK: Taylor and Francis, 1996.

[6] Chanson H. Energy dissipation in hydraulic structures (IAHR Monograph) [M]. Leiden, The Netherlands: Taylor and Francis, 2015.

[7] Vischer D., Hager W. H. Energy dissipators. IAHR Hydraulic Structures Design Manual No. 9, hydraulic design considerations [M]. Rotterdam, The Netherlands: A. A. Balkema, 1995.

[8] Zhang M., Wu Q., Wang G. et al. The flow regime and hydrodynamic performance for a pitching hydrofoil [J]. *Renewable Energy*, 2020, 150: 412-427.

[9] Chanson H. Hydraulic design of stepped cascades, channels, weirs and spillways [M]. Oxford, UK: Pergamon, 1995.

[10] Chanson H. The hydraulics of stepped chutes and spillways [M]. Lisse, The Netherlands: A. A. Balkema, 2001.

[11] Chanson H. Historical development of stepped cascades

for the dissipation of hydraulic energy [J]. *Transactions of the Newcomen Society*, 2000, 72(2): 295-318.
[12] Schuyler J. D. Reservoirs for irrigation, water-power and domestic water supply [M]. 2nd Edition, New York, USA: John Wiley and Sons, 1909.
[13] Wegmann E.. The design and construction of dams [M]. 6th Edition, New York, USA: John Wiley and Sons, 1911.
[14] Sorensen R. M. Stepped spillway hydraulic model investigation [J]. *Journal of Hydraulic Engineering, ASCE*, 1985, 111(12): 1461-1472.
[15] Rajaratnam N. Skimming flow in stepped spillways [J]. *Journal of Hydraulic Engineering, ASCE*, 1990, 116(4): 587-591.
[16] Matos J., Meireles I. Hydraulics of stepped weirs and dam spillways: Engineering challenges, labyrinths of research [C]. *Proceedings of the 5th IAHR International Symposium on Hydraulic Structures (ISHS2014)*, Brisbane, Australia, 2014.
[17] Bombardelli F. A. Computational multi-phase fluid dynamics to address flows past hydraulic structures [C]. *Proceedings of 4th IAHR International Symposium on Hydraulic Structures (ISHS2012)*, Porto, Portugal, 2012.
[18] Chanson H. Hydraulics of aerated flows: Qui pro quo? [J]. *Journal of Hydraulic Research*, 2013: 51(3): 223-243.
[19] 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.
[20] Horner M. W. An analysis of flow on cascades of steps [D]. Doctoral Thesis, Birmingham, UK: University of Birmingham, 1969.
[21] Peyras L., Royet P., Degoutte G. Flow and energy dissipation over stepped gabion weirs [J]. *Journal of Hydraulic Engineering, ASCE*, 1992, 118(5): 707-717.
[22] Chanson H. Hydraulics of skimming flows over stepped channels and spillways [J]. *Journal of Hydraulic Research*, 1994, 32(3): 445-460.
[23] Chanson H. Stepped spillway flows and air entrainment [J]. *Canadian Journal of Civil Engineering*, 1993, 20(3): 422-435.
[24] 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.
[25] Boes R. M., Hager W. H. Two-phase flow characteristics of stepped spillways [J]. *Journal of Hydraulic Engineering, ASCE*, 2003, 129(9): 661-670.
[26] Biethman B., Ettema R., Thornton C. et al. Air entrained in flow along a steep-stepped spillway: Data and insights from a hydraulic model [J]. *Journal of Hydraulic Engineering, ASCE*, 2021, 147(5): 05021001.
[27] Chanson H., Yasuda Y., Ohtsu I. Flow resistance in skimming flows and its modelling [J]. *Canadian Journal of Civil Engineering*, 2002, 29(6): 809-819.
[28] 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, ASCE*, 2017, 143(9): 04017032.
[29] Zabaleta F., Bombardelli F. A. Eddy-resolving simulation of flows over macro-roughness [C]. *River Flow 2020: Proceedings of the 10th Conference on Fluvial Hydraulics*, Delft, The Netherlands, 2020, 1293-1299.
[30] Chanson H. Interactions between a developing boundary layer and the free-surface on a stepped spillway: Hinze Dam Spillway Operation in January 2013 [C]. *Proceedings of 8th International Conference on Multiphase Flow ICMF 2013*, Jeju, Korea, 2013.
[31] Chanson H. Stepped spillway prototype operation, spillway flow and air entrainment: the Hinze Dam, Australia [R]. Hydraulic Model Report No. CH123/21, Brisbane, Australia: The University of Queensland, 2021.
[32] Ervine D. A., Falvey H. T. Behaviour of turbulent water jets in the atmosphere and in plunge pools [J]. *Proceedings of the Institution Civil Engineers, London*, 1987, 83(1): 295-314.
[33] Brocchini M., Peregrine D. H. The dynamics of strong turbulence at free surfaces. Part 1. Description [J]. *Journal Fluid Mechanics*, 2001, 449: 225-254.
[34] Chanson H. Turbulent air-water flows in hydraulic structures: Dynamic similarity and scale effects [J]. *Environmental Fluid Mechanics*, 2009, 9(2): 125-142.
[35] 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.
[36] Chamani M. R., Rajaratnam N. Jet flow on stepped spillways [J]. *Journal of Hydraulic Engineering, ASCE*, 1994, 120(2): 254-259.
[37] Chanson H., and Toombes, L. Hydraulics of stepped chutes: The transition flow [J]. *Journal of Hydraulic Research*, 2004, 42(1): 43-54.
[38] Matos J. Air entrainment and energy dissipation in flow over stepped spillways [D]. Doctoral Thesis, Lisbon, Portugal: Technical University of Lisbon, IST, Lisbon, Portugal, 1999(in Portuguese).
[39] Wűthrich D., Chanson H. Hydraulics, air entrainment and energy dissipation on gabion stepped weir [J]. *Journal of Hydraulic Engineering, ASCE*, 2014, 140(9): 04014046.
[40] 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.
[41] Douma J. H., Goodpasture R. A. Hydraulic model studies for reconstruction of the lahontan dam spillway [R]. Hydraulic Laboratory Report No. HYD-71, Denver, USA: US Bureau of Reclamation, 1940.
[42] Novak P., Cabelka J. Models in hydraulic engineering. physical principles and design applications [M]. London, UK: Pitman Publishing, 1981.
[43] Chanson H., Gonzalez C. A. Physical modelling and scale effects of air-water flows on stepped spillways [J]. *Journal of Zhejiang University SCIENCE*, 2005, 6A(3): 243-250.
[44] 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.
[45] Rodi W., Constantinescu G., Stoesser T. Large-eddy simulation in hydraulics (IAHR monograph) [M]. Leiden, The Netherlands: Taylor and Francis, 2013.
[46] Rodi W. Turbulence modeling and simulation in hydraulics: A historical review [J]. *Journal of Hydraulic Engineering, ASCE*, 2017, 143(5): 03117001.
[47] Prosperetti A., Tryggvason G. Computational methods for multiphase flows [M]. Cambridge, UK: Cambridge University Press, 2009.
[48] Lubin P. Wave breaking and air entrainment. in advanced numerical modelling of wave structure interactions [M]. Boca Raton, USA: Taylor and Francis, 2021, 69-85.
[49] Toro J. P., Bombardellli F. A., Paik J. et al. Characterization of turbulence statistics on the non-aerated skimming flow over stepped spillways: A numerical study [J]. *Environmental Fluid Mechanics*, 2016, 16: 1195-221.

[50] AIAA. Editorial policy statement on numerical accuracy and experimental uncertainty [J]. *AIAA Journal*, 1994, 32(1): 3.
[51] Roache R. L. Verification of codes and calculations [J]. *AIAA Journal*, 1998, 36(5): 696-702.
[52] Rizzi A., Vos J. Toward establishing credibility in computational fluid dynamics simulations [J]. *AIAA Journal*, 1998, 36(5): 668-675.
[53] Ruff J. F., Frizell K. H. Air concentration measurements in highly-turbulent flow on a steeply-sloping chute [C]. New York, USA: *Hydraulic Engineering: Proceedings of the 1994 Conference*, 1994, 999-1003.
[54] Cain P., Wood I. R. Measurements of self-aerated flow on a spillway [J]. *Journal of Hydraulic Division*, 1981, 107(11): 1425-1444.
[55] Wood I. R. Air water flows [C]. *Proceedings 21st IAHR Congress. The International Association for Hydro-Environment Engineering and Research (IAHR)*, Melbourne, Australia, 1985, 18-29.
[56] Rao N., Kobus H., Barczewski B. Characteristics of self-aerated free-surface flows [M]. Berlin, Germany: Erich Schmidt Verlag, 1974.
[57] Chanson H. Air bubble entrainment in free-surface turbulent shear flows [M]. London, UK: Academic Press, 1997.
[58] Crowe C., Sommerfield M., Tsuji Y. Multiphase flows with droplets and particles [M]. Boca Raton, USA: CRC Press, 1998.
[59] Neal L. S., Bankoff S. G. A High resolution resistivity probe for determination of local void properties in gas-liquid flows [J]. *AIChE Journal*, 1963, 9(4): 490-494.
[60] Neal L. S., Bankoff S. G. Local parameters in cocurrent mercury-nitrogen flow [J]. *AIChE Journal*, 1965, 11(4): 624-635.
[61] 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.
[62] Bung D. B., Valero D. Optical flow estimation in aerated flows [J]. *Journal of Hydraulic Research*, 2016, 54(5): 575-580.
[63] 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.
[64] Arosquipa Nina Y., Shi R., Wűthrich D. et al. Intrusive and Non-Intrusive Air-Water Measurements on Stepped Spillways with inclined steps: a Physical Study on Air Entrainment and Energy Dissipation [R]. Hydraulic Model Report No. CH121/21, Brisbane, Australia: The University of Queensland, 2021.
[65] Jones 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.
[66] 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.
[67] 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.
[68] Wang H., Chanson H. Experimental study of turbulent fluctuations in hydraulic jumps [J]. *Journal of Hydraulic Engineering, ASCE*, 2015, 141(7): 04015010.
[69] 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.
[70] Chanson H. Air-water flow measurements with intrusive phase-detection probes. Can we improve their interpretation? [J]. *Journal of Hydraulic Engineering, ASCE*, 2002, 128(3): 252-255.
[71] Tombes L. Experimental study of air-water flow properties on low-gradient stepped cascades [D]. Doctoral Thesis, The Brisbane, Australia: University of Queensland, 2002.
[72] Toombes L., Chanson H. Surface waves and roughness in self-aerated supercritical flow [J]. *Environmental Fluid Mechanics*, 2007, 7(3): 259-270.
[73] Chanson H., Gonzalez C. A. Interactions between free-surface, free-stream turbulence and cavity recirculation in open channel flows: Measurements and turbulence manipulation [C]. *Proceedings 5th International Conference on Multiphase Flow*, Yokohama, Japan, 2004.
[74] 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.
[75] 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.
[76] Sun S., Chanson H. Characteristics of clustered particles in skimming flows on a stepped spillway [J]. *Environmental Fluid Mechanics*, 2013, 13(1): 73-87.
[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.
[78] 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 [R]. Hydraulic Model Report No. CH105/17, Brisbane, Australia: The University of Queensland, 2017.
[79] Kramer M., Valero D., Chanson H. et al. Towards reliable turbulence estimations with phase-detection probes: An adaptive window cross-correlation technique [J]. *Experiments in Fluids*, 2019, 60: 2.
[80] Shi R., Wűthrich 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 AFMC2020*, Brisbane, Australia, 2020.
[81] 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.
[82] Lopes P., Leandro J., Carvalho R. F. et al. Alternating skimming flow over a stepped spillway [J]. *Environmental Fluid Mechanics*, 2017, 17: 303-322.
[83] 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: 375-392.
[84] Chanson H. Hydraulics and energy dissipation on stepped spillways-prototype and laboratory experiences [C]. *Proceedings of the 2nd International Symposium of Water Disaster Mitigation and Water Environment Regulation*, Chengdu, China, 2021.