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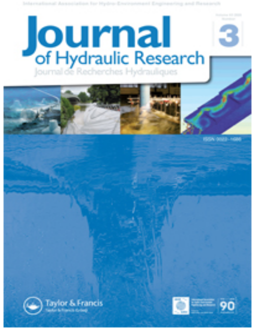

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Hubert Chanson & Davide Wüthrich

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DISCUSSION

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Discussers: Hubert Chanson [a] and Davide Wüthrich [b]

[a]School of Civil Engineering, The University of Queensland, Brisbane, Australia;
[b]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

The Authors developed a state-of-the art review on air–water flows in hydraulic structures. During major floods, the operation of large hydraulic structures is most often characterized and affected by self-aeration (Chanson, 1997; Rao & Kobus, 1974; Wood, 1991). The hydrodynamics of these large air–water flows presents unique challenges with ultra-high-Reynolds numbers, uncontrolled self-aeration and complicated multiphase fluid–structure interactions (Chanson, 2013a; Novak et al., 2007; Vischer & Hager, 1998). The free-surface flows are characterized by ultra-high Reynolds numbers in excess of 10^8 to 10^9 (Figure 1) for which many traditional design assumptions were never validated, e.g. the Moody diagram. The absence of validation data sets obtained in prototype structures is directly linked to the implicit physical limitations of field observations including individual safety and restricted physical access (Chanson, 2013a, 2024; Lin & Han, 2001).

In this discussion, some important issues with the upscaling of air–water flows are addressed and field observations of air–water flows in prototype hydraulic structures are discussed, expanding on the work presented by the review.

Upscaling: from the laboratory to the prototype

The hydraulic modelling of air–water flows may be performed theoretically, physically and numerically. As pointed out in the review paper, most previous studies on air–water flows have been conducted in laboratories at reduced scales. In free-surface flows, gravity effects dominate and a Froude similarity is used (Henderson, 1966; Rouse, 1938). Further, when the same fluids (i.e. air and water) are used in both model and prototype, the Morton number remains invariant (Kobus, 1984). By applying a combined Morton and Froude similarity, the difference in Reynolds numbers between model and prototype accounts for potential scale effects related to both viscous and capillary processes, since the Π-Vaschy-Buckingham theorem implies that the Weber number is no longer relevant (Pfister & Chanson, 2014).

When dealing with small scale physical modelling a critical question arises: what is the largest acceptable geometry scaling ratio L_r, defined as the ratio of prototype to model dimensions? Two seminal textbooks on air–water flows recommended: $L_r < 10$ (Chanson, 1997; Wood, 1991). However, a detailed model-prototype comparison of air-regulated siphon spillway demonstrated that even a large-size physical model with $L_r = 5$ failed to accurately predict the rating curve and air entrainment rate observed in the prototype structure, indicating that "models may give misleading information about full-scale behavior" (Ervine & Oliver, 1980). Importantly, any discussion on upscaling and scale effects in air–water flows must be rigorous. The notion of scale effects and model-prototype compliance must be closely linked to the selection of the criterion (or criteria) to assess scale affects (Chanson, 2009). It has been known for decades that some air–water flow properties are more affected by scale effects than others (Chanson, 2009; Rao & Kobus, 1974; Wood, 1991). For example, Estrella et al. (2022) analysed a broad range of hydraulic and air–water flow properties in hydraulic jumps with constant inflow Froude ($\mathrm{Fr} = 2.1$) and Morton numbers ($\mathrm{Mo} = 2.5 \times 10^{-11}$), but different Reynolds numbers ($7.75 \times 10^3 < \mathrm{Re} < 3.05 \times 10^5$), as displayed in Figure 2. Ultimately, in line with the few systematic comparisons available, these results confirmed that certain air–water properties (e.g. void fraction and interfacial velocities) scale better than others (e.g. bubble characteristics), which cannot be reliably extrapolated from laboratory studies to full scale without further investigation (Chanson, 2013a; Rao & Kobus, 1974). Direct guidelines on what can be obtained and what cannot be obtained with small-size models were developed by Chanson and Chachereau (2013, table 2), Wang and Chanson (2016, table 2) and Estrella et al. (2022, table 2) for air–water flows in hydraulic jumps, and Chanson and Gonzalez (2005,

CONTACT Davide Wüthrich h.chanson@uq.edu.au

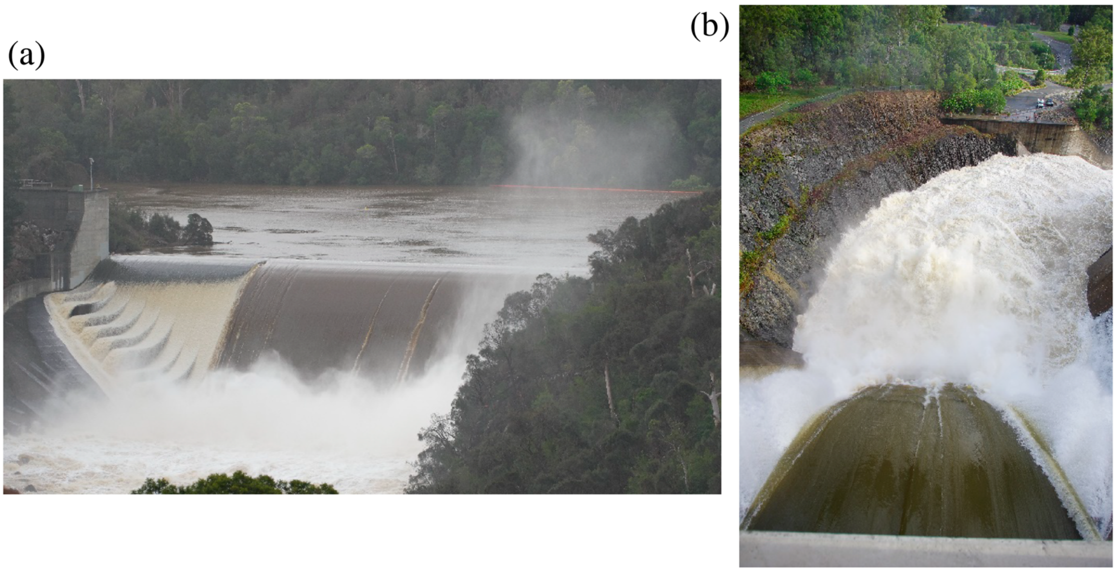

Figure 1. Hydraulic structure operations during major floods (photographs by Hubert Chanson). (a) Trevallyn Dam discharging 532 m^3 s^{-1} with Re $= 2.0 \times 10^7$ – photograph shutter speed: 1/250 s, aperture: f/6.3. (b) Hinze Dam spillway discharging 340 m^3 s^{-1} with Re $= 1.1 \times 10^8$ – photograph shutter speed: 1/500 s, aperture: f/5.6.

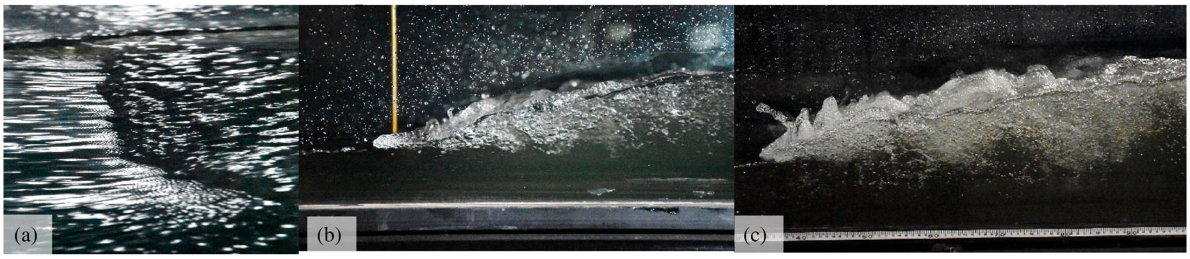

Figure 2. Hydraulic jumps with Fr $= 2.1$ for different scales: (a) Re $= 7.8 \cdot 10^3$; (b) Re $= 6.3 \cdot 10^4$; (c) Re $= 2.0 \cdot 10^5$ (after Estrella et al. 2022).

(a) (b)

Figure 3. Air–water flows at hydraulic structures. (a) Aviemore Dam spillway chute in operation – photograph shutter speed: 1/160 s, aperture: f/5.6 (photograph provided by Meridian, New Zealand) (b) Chinchilla Weir discharging 161 m^3 s^{-1} with Re $= 3 \times 10^6$ – photograph shutter speed: 1/8000 s, aperture: f/2.8 (photograph by Hubert Chanson).

p. 249) and Felder and Chanson (2017, table 4) for self-aerated stepped chute flows.

A complete absence of scale effects is only observed in air–water flows in prototype flow conditions, i.e. at full-scale hydraulic structures. The importance of field measurements has repeatedly been emphasized by leading scholars (Chanson, 2013a; Kolkman, 1984; Novak, 1984; Novak et al., 2010). The air–water flow literature does include a number of seminal prototype data sets: at the Aviemore Dam spillway on the air–water flow structure and air–water flow properties (Cain & Wood, 1981; Keller, 1972) (Figure 3a); at the Hinze Dam stepped spillway on the mechanisms of self-aeration and energy dissipation (Chanson, 2013b, 2022; Chanson & Hu, 2024) (Figure 1b); and at the Chinchilla Weir converging chute on the velocity and turbulence fields in the air–water flow region (Chanson & Apelt, 2023) (Figure 3b). A few other prototype spillway tests were reported by Falvey (1982), Volkart and Rutschman (1984), and Bai et al. (2021). Several papers discussed the difficulties, intricacies and limitations of field observations of air–water flows (Chanson & Shi, 2024; Jevdjevich & Levin, 1953; Michels & Lovely, 1953; de Pinto et al., 1982), and the first author (HC) experienced first-hand the practical difficulties of conducting tests at Gold Creek Dam and Paradise Dam. The challenges cannot be ignored. However, it is of principal importance that, whenever possible, any new development in air–water flows must be validated against seminal prototype data to gain a broad acceptance among the industry.

Finally, in prototype hydraulic structures, the overflow often consists of a three-phase mix of water, air and sediments (Bombardelli & Chanson, 2009, 2017; Chanson, 2013). During floods, the sediment load is large and the multiphase gas–liquid–solid flows are complex, with multi-level multi-phase interactions (Balachandar & Eaton, 2010; Hanratty et al., 2003; Prosperetti & Tryggvason, 2009). In the presence of floating debris sometimes transported by the flood waters, major accidents might further happen, and the interactions between large debris and air–water flows remain unknown. Arguably, the research and development community faces some massive challenges ahead with air–water flow modelling, both physically and computationally.

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No potential conflict of interest was reported by the author(s).

Notation

Fr	inflow Froude number (−)
L_r	geometric scaling ratio, defined as the ratio of prototype to model dimensions (−)
Mo	Morton number (−)
Re	Reynolds number (−)

ORCID

Hubert Chanson http://orcid.org/0000-0002-2016-9650
Davide Wüthrich http://orcid.org/0000-0003-1974-3560

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