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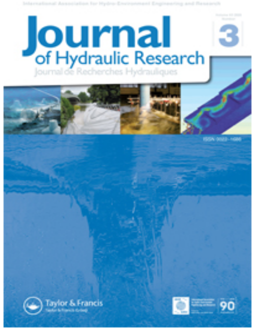

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DISCUSSION

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Discussion of 'Air–water flows'

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The Authors present a comprehensive review of air–water flows in hydraulic structures, offering a detailed overview of advancements made over the past two decades in steady fast-moving flows. This knowledge holds significant relevance for practitioners and researchers, as they continuously strive to develop novel approaches for designing efficient and sustainable hydraulic (infra)structure (Erpicum et al., 2021). In the face of a changing climate, hydraulic structures play an increasingly vital role in enhancing community resilience. Studies indicate that flows associated with extreme natural disasters will become more frequent and more severe in the future (Dottori et al., 2020), as evidenced by the destructive 2021 floods in Germany, Belgium, and the Netherlands (Wüthrich et al., 2025). These recent events underscore two key characteristics: (1) the unsteady nature of such extreme occurrences, and (2) their complex, multiphase composition involving air, sediments and (floating) debris. In this Discussion, recent advances in the computation of air–water flow properties in unsteady flow conditions are presented and discussed, which complement the review provided by the Authors. In addition, a comparison between steady and unsteady flows is presented, hinting on the importance of upscaling air–water measurements against the (few) available field observations.

Highly unsteady multiphase flows are typical in breaking bores, flash-floods, tsunamis and storm surges (e.g. Figure 1). In these flows the free surface is highly fragmented, with abrupt motions and strong turbulence that generate continuous interactions between the gas and liquid phases (Chanson 2013). These dynamics create distinctive interfacial features, described by Brocchini and Peregrine (2001) and Wüthrich et al. (2021). Often termed "hydraulic jumps in translation", these transient flows exhibit characteristics similar to hydraulic jumps (Lubin & Chanson, 2017; Wüthrich et al., 2022b). As highlighted by the Authors, steady flows can count on long duration measurements (typically 45 s or longer). However, this approach cannot be applied to fast-moving highly-transient flows. Instead, a paradigm shift is needed, involving multiple repetitions and ensemble statistics to accurately capture these unsteady phenomena (Chanson, 2020; Leng & Chanson, 2019; Wüthrich et al., 2022a). Extensive measurements of transient air–water flows were undertaken in sudden (flash-flood) flows on stepped slopes (Chanson, 2004), dam-break waves (Regout et al., 2025) and breaking bores (Leng & Chanson, 2019; Wüthrich et al., 2022a). These studies conducted detailed experiments using an array of multiple phase detection (conductivity) probes sampled at very-high-frequency (100 kHz), where one reference probe was used to synchronize all repetitions, while the others investigated the air–water flow properties at various elevations. By combining multiple configurations, this approach delivered a comprehensive reconstruction of the air–water flow characteristics, including bubble dynamics, void fractions and turbulent characteristics. Wüthrich et al. (2021) performed a detailed sensitivity analysis, revealing that 50 to 100 repetitions are necessary to obtain physically meaningful and statistically reliable values for various air–water flow properties.

The data for two flow conditions in Figure 2 showed that the ensemble-median number of interfaces N (representing the detected phase transitions between air and water, thus correlating with bubble counts) varied throughout the bore's depth, reaching its maximum within the shear layer. The bubbles chord length $L_{ch} = U \cdot t_{ch}$ (where U is bore front celerity and t_{ch} the bubble chord time) also displayed variability across the bore height, with larger bubbles found predominantly in the upper recirculation zone. Both findings show similarities with stationary hydraulic jumps, revealing the suitability of the ensemble approach to study highly unsteady flows.

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(a)

(b)

Figure 1. Breaking bores: (a) tidal bore of the Qiantang River on 12 October 2014 propagating from right to left (photo by H. Chanson, 1/1600s, f5.6); (b) breaking bore in the laboratory $Fr_1 = 2.1$ propagating from background to foreground (photo by D. Wüthrich, 1/1800s, f3.5).

Using an analytical solution of the advection–diffusion equation, Chanson (2004) showed that the vertical distribution of void fractions at the leading edge of an unsteady flow exhibits a convex profile, where the entrained and entrapped air pockets are mainly subjected to buoyancy, drag and gravitational forces, therefore explaining the high depth-averaged void fractions. Wüthrich et al. (2022a) reported similar observations for a breaking bore propagating over an initial flow depth d_1, with the behaviour of the void fraction C well captured by the equation (Shi et al., 2023b):

$$C = 0.9 \cdot \left(\frac{z - d_1}{Z_{90} - d_1} \right)^n \quad (1)$$

where z is the vertical coordinate and Z_{90} is the characteristic elevation where $C = 90\%$. The exponent n is related to the depth-averaged void fraction C_{mean} in the roller through:

$$C_{mean} = \frac{1}{Z_{90}} \int_0^{Z_{90}} C dz = \frac{0.9}{n + 1} \quad (2)$$

The agreement between Equation (1) and experimental data is showcased in Figure 3a for breaking bores (Shi et al., 2023b; Wüthrich et al., 2022a) for $T \cdot U/d_1 < 0.6$. A similar agreement was observed in the dam-break wave datasets of Chanson (2004) and Regout et al. (2025), at nappe impact of drop structures and bottom aeration devices (Chanson, 1988; Toombes & Chanson, 2008) and in the hydraulic jump of Estrella et al. (2022) and Wüthrich et al. (2022b) for low Froude numbers $Fr_1 = 2.1$ and 2.4, as shown in Figure 3c. This highlights the existence of this convex air–water profile across a wide range of physical processes in both highly fragmented steady and unsteady flow conditions, as well as the suitability of Equation (1) to describe it.

Further downstream, air pockets began to interact with the turbulent structures, breaking into finer pieces and marking the transition to a concave profile, which corresponds to lower depth-averaged void fractions. Figure 3a and c illustrate how the initial convex profile transitions into a concave profile, aligning well with the typical steady flow profiles discussed by the Authors. Notably, Shi et al. (2023b) identified the

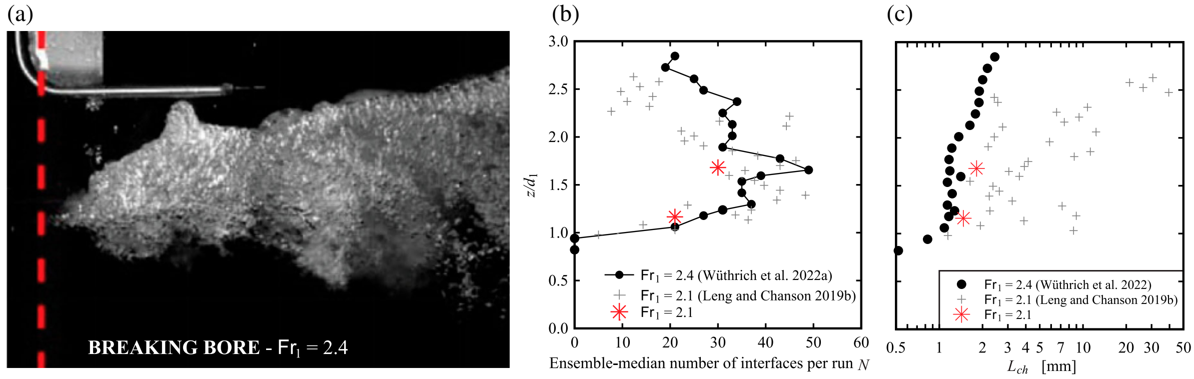

Figure 2. Bubble characteristics in unsteady breaking bores: (a) image of bore with $Fr_1 = 2.1$ (Shi et al. 2023b); (b) ensemble median number of interfaces; (c) median bubble chord time $L_{ch} = U \cdot t_{ch}$, with U = bore celerity and t_{ch} = bubble chord time (interval between water–air and air–water interface).

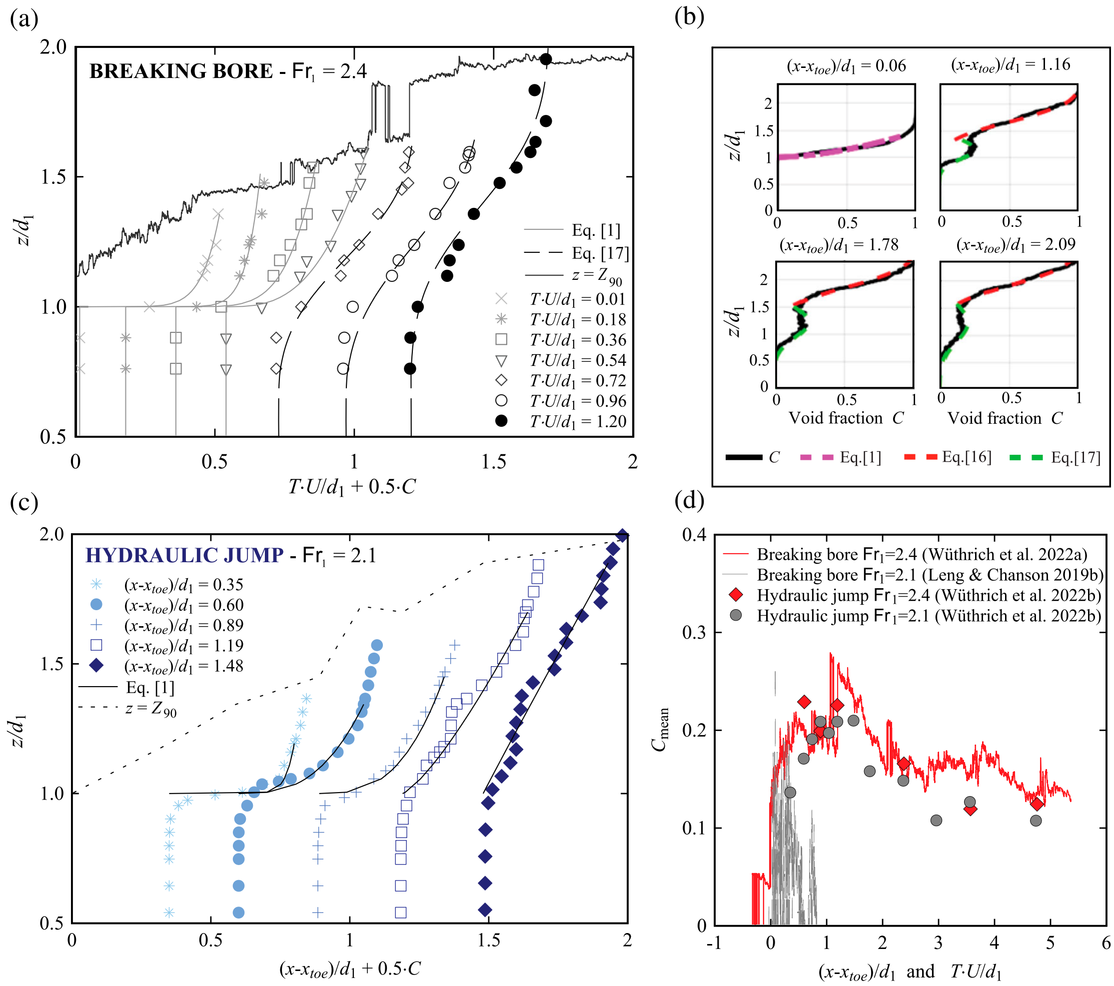

Figure 3. Results for air–water measurements: (a) void fraction profiles obtained with conductivity probes for a breaking bore with $Fr_1 = 2.4$ using ensemble-average analysis (Wüthrich et al. 2022a); (b) void fraction profiles for a breaking bore with $Fr_1 = 2.4$ obtained with EBDT (Shi et al. 2023b); (c) void fraction profiles for a stationary hydraulic jumps with $Fr_1 = 2.1$ (Wüthrich et al. 2022b), where x_{toe} represents the position of its roller toe; (d) comparison of depth-averaged void fraction C_{mean} for breaking bores and hydraulic jumps. Note that Equations (16) and (17) refer to the original manuscript by Valero et al. (2024).

presence of a shear layer in the breaking bores (Figure 3b), followed by a recirculation zone where profiles typical of hydraulic jumps appear, as described by Equations (16) and (17) listed by Valero et al. (2024). These observations further underscore similarities between breaking bores and hydraulic jumps (Lubin & Chanson, 2017), sustained by the comparison conducted for low Froude numbers ($\mathsf{Fr}_1 = 2.1$ and 2.4) in Figure 3d, showing excellent agreement.

As highlighted by the Authors (Valero et al., 2024), imaging techniques in air–water research have gained popularity, particularly for highly unsteady flows, where ultra-high-speed videos can offer both spatial and temporal insights into the dynamics of rapidly evolving air–water features. These techniques show great promise. For instance, a novel enclosed bubble detection technique (EBDT) showed the ability to detect individual bubbles within the breaking roller, enabling detailed analysis of void fraction and bubble properties, as illustrated in Figure 3c (Shi et al., 2023b). In terms of velocity and turbulence characteristics, Shi et al. (2023a) introduced the single bubble event detection (SBED) technique, which computes pseudo-instantaneous interfacial velocities for individual bubbles in unsteady flows, in line with the segmentation framework of Kramer et al. (2019). The SBED technique showed good agreement with velocity data derived from image-based optical flow (OF) and particle tracking velocimetry (PTV). However, while the non-intrusive nature of image-based approaches is advantageous, they are generally restricted to the sidewalls and data may be affected by sidewall effects, where fewer bubbles, lower void fraction, and reduced velocities have been reported (Wüthrich et al., 2022b; Zhang & Chanson, 2018). Despite inherent limitations, these methods might collectively provide, when used alongside intrusive probe measurements, a comparative analysis of multiphase and turbulent features, underscoring the importance of redundant measurements when investigating highly unsteady flows.

Altogether, these results showcase the effectiveness of the ensemble approach to obtain air–water flow properties in highly unsteady flows, revealing similarities between steady and unsteady flows, which can provide new and helpful insights to understand the underlying physics of unsteady phenomena. Ultimately, the collection of detailed data on the multiphase nature of unsteady flows will facilitate the development of robust validation datasets for computational fluid dynamics (CFD) modelling (e.g. Bombardelli, 2012; Leng et al., 2018; Prosperetti & Tryggvason, 2009) and full-scale extrapolation (e.g. Figure 1a).

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Disclosure statement

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Notations

C	void fraction (–)
C_{mean}	depth-averaged void fraction (–)
d_1	initial water depth (m)
Fr_1	Froude number, $\mathsf{Fr}_1 = U/(gd_1)^{0.5}$ (–)
g	gravitational constant, $g = 9.81$ (m s^{-2})
L_{ch}	ensemble-median bubble chord length, defined as $L_{ch} = U \cdot t_{ch}$ (m)
n	exponent (–)
N	ensemble-median number of interfaces (–)
T	time (s)
t_{ch}	bubble chord time (s)
U	bore front celerity (m s^{-1})
x	longitudinal (streamwise) coordinate (m)
x_{toe}	position of the roller toe in hydraulic jumps (m)
z	vertical coordinate (m)
Z_{90}	elevation where $C = 0.9$ (m)

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