

VOID FRACTION IN HIGHLY UNSTEADY AIR-WATER FLOWS

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INTRODUCTION

Highly unsteady flows, characterized by long-period, high-translatory waves, are common in nature. They describe coastal phenomena like tsunamis, storm surges, and flood waves, as well as more inland events such as tidal bores and dam failures. Recent incidents have shown that these phenomena significantly threaten densely populated coastal and riverine areas, with their frequency increasing globally due to climate change and sea level rise. Therefore, obtaining a deeper understanding of the physical processes behind their hydrodynamic behavior is necessary.

Due to abrupt discontinuities in water level, velocities, and pressures when propagating into shallow waters, these highly unsteady flows are associated with a breaking roller at the front, characterized by a strong recirculating air-water mixture (Figure 1). The interaction between air and water, known as multiphase flow, involves dynamic processes including viscous, capillary, and gravitational effects, leading to turbulent motion and the formation of eddies and bubble structures (Brocchini and Peregrine, 2001). Hence, the presence of large amounts of air in the breaking roller significantly influences the hydrodynamic characteristics.

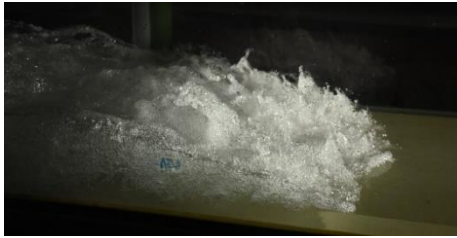


Figure 1- Recirculating air-water mixture in breaking roller

Many experimental studies looked at the air-water flow properties of multiphase flows and observed distinct regions across the roller, influenced by different mechanisms. Studies on (steady) hydraulic jumps have identified an upper recirculating zone and a lower shear layer, linked to differences in air distributions over height. Consequently, several analytical models have been developed to define these profiles based on advection-diffusion processes (e.g. Chanson 1989, 1995). However, most previous research focused on steady flows such as hydraulic jumps and spillway flows. Research on unsteady flows is still very limited, mostly relying on small datasets and few flow conditions. This lack of diversity in the experimental data hinders a broad understanding of the multiphase behavior of unsteady flows, restricting the development of numerical models to accurately incorporate air, highlighting the need for future research.

In this context, this experimental study analyzes multiphase characteristics in the breaking roller under various hydrodynamic conditions. Since the analogy with dam-break waves is commonly used to describe unsteady long-period wave phenomena (Chanson et al., 2003), this

study focuses on the air-water flow properties of dam-break waves over varying tailwater depths, with a specific focus on the void fraction distribution.

EXPERIMENTAL SET-UP AND METHODOLOGY

A series of new experiments were conducted at the hydraulic laboratory of TU Delft, where dam-break waves were generated in a flume 39m long, 0.76m wide, and 0.85m deep. A newly designed pneumatic lift gate system created an abrupt opening (Figure 2), releasing a large volume of water to produce a dam-break wave propagating over a still tailwater depth with a celerity (U). Different flow conditions were achieved by varying the initial downstream water depth (h_0) while maintaining a constant impoundment depth (d_0) of 0.8m for all tests. The flow conditions considered are summarized in Table 1, with Froude and Reynolds numbers defined as:

$$Fr = \frac{U}{\sqrt{g \cdot h_0}} \quad (1), \quad \text{and} \quad Re = \frac{\rho \cdot U \cdot h_0}{\mu} \quad (2).$$

Table 1 - Test program and flow conditions

flow condition	h_0 [mm]	h_0/d_0	Fr	Re
FC1	32	0.04	5.4	$0.97 \cdot 10^5$
FC2	64	0.08	3.6	$1.81 \cdot 10^5$
FC3	96	0.12	2.8	$2.63 \cdot 10^5$
FC4	128	0.16	2.4	$3.44 \cdot 10^5$

Four Acoustic Displacement Meters (ADMs) were equally spaced in longitudinal direction to measure the wave's hydrodynamic characteristics. An array of four phase-detection conductivity probes was used to measure the air-water flow properties by detecting changes in conductivity values, distinguishing between air (low conductivity) and water (high conductivity). The probes were positioned in parallel at various elevations, with their tips facing the incoming waves (Figure 2).

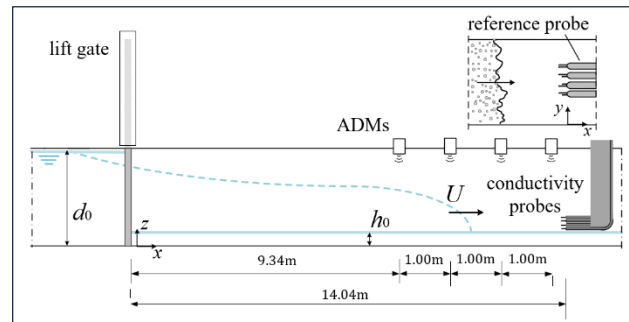


Figure 2 - Experimental set-up

All probes were sampled simultaneously at 100kHz. Each flow condition included four different probe configurations, covering a total of 13 different elevations ($h_0 - 10\text{mm} \leq z \leq h_0 + 210\text{mm}$). Herein, three probes were shifted in the vertical direction, while a reference probe remained fixed 5mm above the initial water level, to synchronize all tests.

The unsteadiness of the flow prevents the possibility to obtain long-duration measurements. Consequently, data analysis was based on ensemble-averaging techniques, requiring a sufficient number of repetitions (Wüthrich et al., 2022). A total of 220 repetitions was performed for each flow condition, with each elevation tested 55 times. Applying a single threshold technique (Wüthrich and Regout 2024), the post-processed binarized signal of a single probe tip presents the instantaneous void fraction at the corresponding elevation in the roller ($0=\text{air}$, $1=\text{water}$). Subsequently, the ensemble-averaged void fraction $C(z, t)$ is derived by averaging the 55 signals obtained at each elevation, i.e. the maximum likelihood that air is present at a specific location and time.

PRELIMINARY RESULTS

The void fraction $C(z, t)$ is obtained for all flow conditions showing similar results, as illustrated by a contour plot for FC1 in Figure 3. It shows the various air concentration levels across the roller, along with z_{90} , which indicates elevations where $C(z, t)=0.9$, typically used as a definition of the free-surface level in air-water flows.

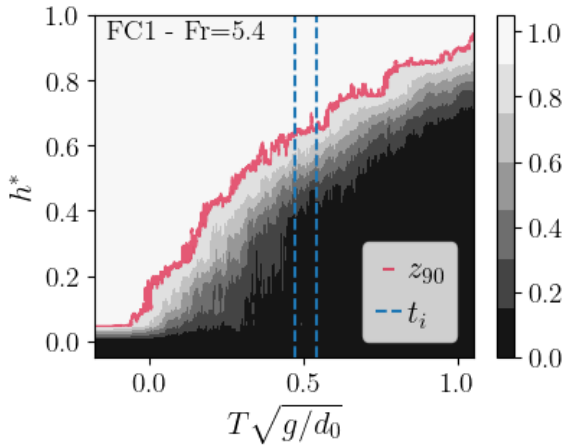


Figure 3 - Contour plot of void fraction for FC1

Figure 4 shows the ensemble averaged void fraction profile at selected time instances $t=0.473, 0.543$ as a function of the roller height, compared with analytical solutions for the upper recirculating zone (Chanson, 1989) and the lower shear layer (Chanson, 1995). For $h^* < 0.4$, the experimental data shows a local increase in C , indicating a turbulent shear layer in the lower part of the roller. At higher elevations, a typical S-shape was found, representing the recirculation zone near the surface. The good agreement between the data and theoretical models confirms the presence of these distinct regions, a behavior consistent with previous observations in hydraulic jumps.

To compare different flow conditions, the depth-averaged void fraction $C_{\text{mean},z}$ is derived by integrating C between $z=0$ and $z=z_{90}$ at each time step, with the results shown in Figure 5. Higher peaks of depth-averaged void fraction were found for increasing Froude numbers, with a peak value of $C_{\text{mean},z} \approx 23\%$ for FC4 and $C_{\text{mean},z} \approx 39\%$ for FC1. Overall, these preliminary results support the use

of this novel methodology to quantify and analyze the air distribution in unsteady flows, providing a deeper understanding of their multiphase nature in the breaking roller.

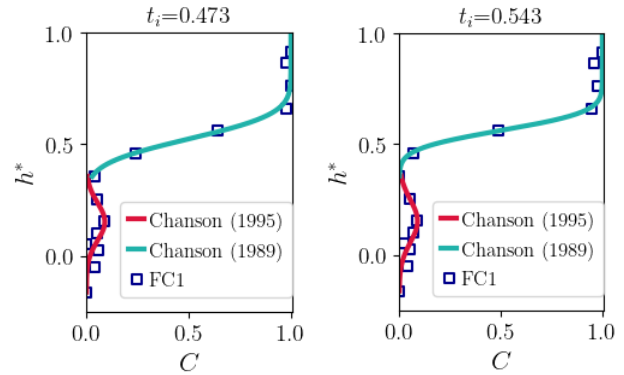


Figure 4 - Void fraction profiles (FC1) at $T\sqrt{g/d_0}=t_i$, compared with theoretical advection-diffusion models.

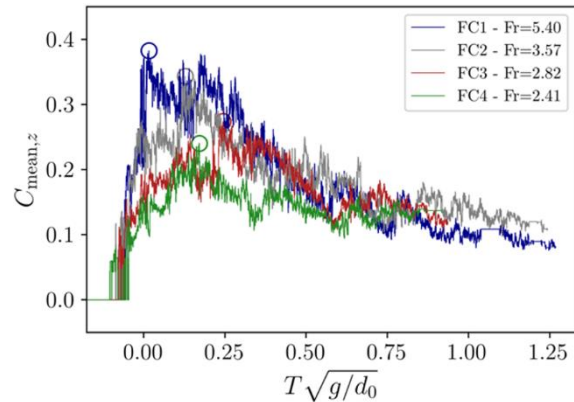


Figure 5 - Comparison of depth-averaged void fraction

REFERENCES

- Brocchini, Peregrine (2001). The dynamics of strong turbulence at free surfaces. Part 1. Description. *Journal of Fluid Mechanics*, 449, 225-254.
- Chanson, Aoki, Maruyama (2003). An experimental study of tsunami runup on dry and wet horizontal coastlines. *Science of Tsunami Hazards*, 20, 278-290.
- Chanson (1989). Study of air entrainment and aeration devices. *Journal of Hydraulic Research* 27, 301-319.
- Chanson (1995). Air entrainment in two-dimensional turbulent shear flows with partially developed inflow conditions. *Int. Journal of Multiphase Flow* 21, 1107-1121.
- Wüthrich, Shi, Chanson (2022). Ensemble-statistical approach in the measurement of air-water flow properties in highly unsteady breaking bores. *Review of Scientific Instruments*, 93(5), 054502.
- Wüthrich, Regout (2024). Air-water flow properties in dam-break waves: a sensitivity analysis. *Proceedings of the 10th International Symposium on Hydraulic Structures*, Zurich, Switzerland, 17-19 June.