Self-aeration and Surface Velocities in Ultra-High Reynolds Number Free-Surface Flows

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Introduction

A seminal turbulent flow is the free-surface flow above an un-controlled spillway chute. The open channel flow constitutes a highly-turbulent high-speed motion with Reynolds numbers ranging from 10^6 to over 10^9. At the upstream end, the rapidly accelerated flow exhibits a glossy free-surface. A turbulent boundary layer develops along the invert. Once the outer edges of the boundary layer interact with the water surface, self-aeration develops with strong air-water ejections and intense air entrainment.

Despite detailed laboratory works, our knowledge of ultra-high Reynolds number free-surface flows is thin: *"what do we know about prototype spillway operation during major floods? "*

Figure 1: Self-aeration at Chinchilla MEL weir spillway in 2024 - High shutter speed photograph (1/8,000 s).

Study site and field measurements

The Chinchilla Weir is a large dam located on the Condamine River [1]. The catchment area is 19,192 km^2. The 14 m high dam is a embankment with an uncontrolled spillway chute (Fig. 1). The spillway structure consists of an un-gated 214 m long broad crest followed by a smooth converging chute on the 1V:5H downstream slope. The downstream energy dissipation takes place in the form of a hydraulic jump above the chute toe, without apron.

Photographic and cinematographic observations were conducted between 1997 and 2024 [2,3]. The records focused on the self-aeration, including optical flow (OF) measurements, obtained at relatively large Reynolds numbers..

References

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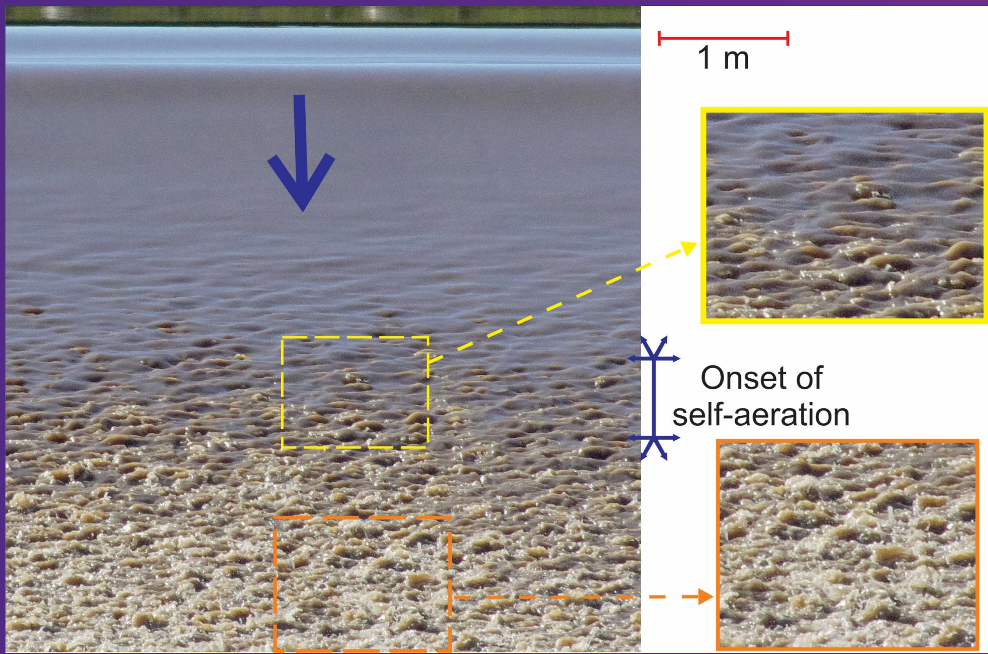

Figure 2: Onset of self-aeration - High-shutter speed photograph (1/8,000 s) for Re = 3×10^6. Flow direction from top to bottom.

Results

Visual and aerial photography showed that the reservoir inflow approached very smoothly the dam crest. The overflow accelerated rapidly down the steep chute. With increasing distance, surface scars began to appear at the free-surface (Fig. 2). Three-dimensional surface waviness and scars resulted from large-scale turbulence at the outer edge of the developing boundary layer.

Once the turbulence level exceeded the resultant of capillary and gravity resistance, self-aeration and intense air-water mixing took place (Figs. 2 & 3).

Figure 3: Details of high-velocity self-aerated free-surface flow - High-shutter speed photograph (1/8,000 s) for Re = 3×10^6. Flow direction from top left to bottom right.

Intense air-water surface turbulence

Long-exposure photography and stacked video imaging highlighted the extremely complicated nature of the air-water surface region in the high-Reynolds number flows, with intense mixing throughout the air-water column. The air-water surface was a highly turbulent region corresponding to the outer edge of the boundary layer region.

The velocity field may be analysed theoretically in the developing flow region based upon the momentum integral equation and using energy considerations in the fully-developed air-water flow region. The calculations showed a close agreement in term of the surface velocity with optical flow surface velocity data measured during flood events.

Conclusions

There is a critical need for ultra-high Reynolds number high-velocity free-surface flow data sets. The knowledge gap has been very rarely addressed, owing to the complexity of turbulent and multiphase flow processes at large scales.

1. At Chinchilla Weir chute, the interactions of the developing turbulent layer with the free-surface led to complicated air-water surface patterns (Figs. 2 & 3).
2. Theoretical calculations of surface velocity profiles presented a close agreement with optical flow data measured during two flood events.

During natural disasters, what do we know about flood mitigation structure fluid flow? **Not enough!**

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