

CASE STUDY

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Prototype spillway experience during large floods: extraordinary high Reynolds number overflow events

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ABSTRACT

During major floods, large dams can discharge very high-velocity free-surface flows with extraordinary high Reynolds number ($Re > 10^8$). Quantitative observations of large flood events are extremely rare and constitute a major knowledge gap. In this contribution, the operation of three large dam spillways is reviewed for flow conditions at extraordinary high Reynolds numbers. All the spillways were un-gated, equipped with an ogee crest, followed by a steep chute and energy dissipator. On the spillway chute, the flow accelerated, transient elongated vortices were observed, and the water surface became choppy, before becoming self-aerated. At the inception region of free-surface aeration, dynamic interactions between large-scale turbulent structures and the free-surface were seen. The inception region was well-marked and a robust correlation for the aeration inception location was derived at extraordinary high Reynolds numbers. Intense free-surface aeration was observed downstream of inception, with complex three-phase coupling between air, water and sediments, as well as air–water surface waves in the energy dissipator.

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1. Introduction

Dams and reservoirs are essential for the provision of reliable water supplies and flood protection (ICOLD, 1984). Prototype data sets of large dam operation are scarce during major floods, although more than one third of dam failures were linked to spillway deficiencies and lack of spillway capacity (Schnitter, 1993). Quantitative observations at large dam spillways during major floods remain extremely rare (Elder, 1984, 1986; Burgi & Gao, 2001), despite some recent field data sets in China (Lin & Han, 2001; Bai et al., 2021) and in Australia (Chanson & Apelt, 2023; Chanson, 2024, 2026). Prototype tests under controlled conditions can provide valuable data under idealized situations with relatively large Reynolds numbers (not flood flows), although the intrinsic limitations must be well understood (Elder, 1984; Chanson, 2013).

During large flood events, most spillways operate as high-velocity free-surface flows with extraordinary high Reynolds number, i.e. $Re > 10^8$ (Figure 1). The expressions ‘high Reynolds numbers’ and ‘very high Reynolds numbers’ are used in the fluid mechanics literature to describe flow conditions with bulk Reynolds numbers about 10^5 to 10^6 (Sanders et al., 2006; Smits et al., 2013; Vallikivi et al., 2015). During a large flood, the spillway flow conditions correspond to Reynolds numbers much larger than traditional fluid mechanics and hydraulics applications, including fighter jets at supersonic speeds and large pipelines

at full capacity. Herein, the expression ‘extraordinary high Reynolds number’ is used. Further, the Moody diagram is based upon experimental data obtained with Reynolds numbers less than 10^8 (Moody, 1944), and recent experimental developments (McKeon et al., 2004, 2005; Furuichi et al., 2015; Ono et al., 2025) were limited to Reynolds numbers less than 7×10^7 . Many air–water flow relationships used in spillway design were based upon and validated with laboratory experiments and prototypes tests, e.g. Aviemore Dam, obtained for $Re < 2 \times 10^7$ (Cain & Wood, 1981; Wood, 1991; Chanson, 1997). Thus, the threshold $Re > 10^8$ is used herein to define ‘extraordinary high Reynolds number’. Figure 1 illustrates three large dams operating with large overflow conditions corresponding to events smaller than 20% of their design discharge and less than 10% of their probable maximum flood (PMF). Even larger flows are hence possible than those described in the article. The flow conditions are listed in the figure caption (Figure 1), the design discharges are listed in Table 1, and the respective locations of the structures are shown in Figure 1D. All these spillways are un-gated, a design that is considered the ‘safest’ spillway design (Cassidy & Elder, 1984).

Field measurements and prototype observations during large floods remain the only way to completely confirm the validity of theoretical, numerical and physical modelling results (Novak et al., 2010). Spillways of large dams are designed for extreme events, but it is

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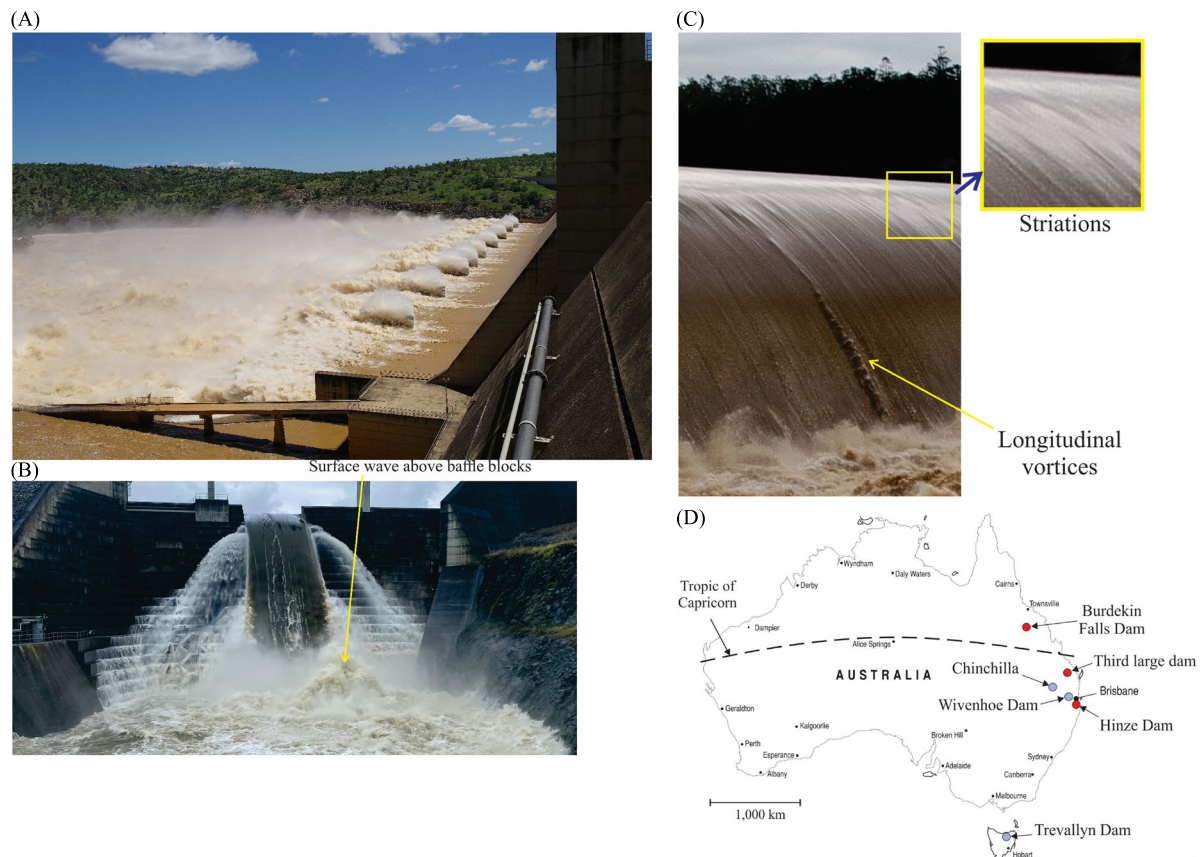


Figure 1. Prototype spillway operations during large overflows (Photographs Hubert Chanson). (A) Burdekin Falls Dam spillway (North Queensland, Australia) – $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, shutter speed: $1/2000 \text{ s}$, aperture f4, 13 February 2025. (B) Hinze Dam spillway (south-east Queensland, Australia) – $Q = 273 \text{ m}^3 \text{ s}^{-1}$, $Re = 8.9 \times 10^7$, shutter speed: $1/8000 \text{ s}$, aperture f2.4, 10 March 2025. (C) Third large dam spillway (Central Queensland, Australia), $Q = 5965 \text{ m}^3 \text{ s}^{-1}$, $Re = 7.1 \times 10^7$, shutter speed: $1/160 \text{ s}$, aperture f14, 30 December 2010 – inset: details of free-surface striations. (D) Map of Australia with the locations of several larger dams: i.e. Burdekin Falls Dam, Hinze Dam and the third large dam, as well as Trevallyn Dam, Wivenhoe Dam and Chinchilla Weir.

Table 1. Prototype spillway characteristics.

	Burdekin Falls Dam	Hinze Dam	Third large dam ²
Location	North Queensland, Australia	South-east Queensland, Australia	Central Queensland, Australia
Design discharge Q_{des}	$64,600 \text{ m}^3 \text{ s}^{-1}$	$4060 \text{ m}^3 \text{ s}^{-1}$	$93,500 \text{ m}^3 \text{ s}^{-1}$
Spillway crest ¹	Ogee	Ogee with few small steps ($h = 0.5 \text{ m}$)	Ogee with few small steps
Spillway chute ¹	Smooth chute ($\theta = 49.0^\circ$, $B = 504 \text{ m}$)	Stepped chute ($\theta = 51.3^\circ$, $B = 12.25 \text{ m}$, $h = 1.5 \text{ m}$)	Stepped chute ($\theta = 57.4^\circ$, $B = 315 \text{ m}$, $h = 0.62 \text{ m}$)
Energy dissipator	Ski jump	Hydraulic jump stilling basin with baffle blocks	Plunge pool
Observation period ³	February 2025	2013–2025	2010–2013

Notes: B , chute breadth; h , vertical step height; Q_{des} , design discharge; θ , chute slope; ¹primary spillway; ²original dam spillway; ³present analyses.

difficult to quantitatively document their performances under such design conditions. This is linked to the rarity of large flow events, the restricted access during floods and a lack of permanent remotely operated instrumentation (Elder, 1986; Chanson & Shi, 2024).

Today, a major knowledge gap for large dam spillways is the lack of prototype validation data sets and field investigations during major floods with extraordinary high Reynolds numbers (i.e. $Re > 10^8$). In such extraordinary high Reynolds number flow conditions, many theoretical considerations have not been validated and the turbulent multiphase flow processes are complicated.

In this contribution, the operations of three large dams, overflowing with extraordinary high Reynolds numbers, are reviewed and discussed, based upon a number of field observations conducted between 2010 and 2025. All the spillways were un-gated and equipped with an ogee crest. The field data highlighted unusual free-surface features as well as an intense free-surface aeration, rarely documented qualitatively and quantitatively at extraordinary high Reynolds numbers. Key features of the free-surface flow in the developing flow region, of the onset of self-aeration, and of the air–water flows are described and quantitatively documented.

2. Case studies

2.1. Prototype spillways

The prototype observations were conducted at three large dam spillways located in eastern Australia (Table 1, Figure 1D). Completed in 1987, the Burdekin Falls Dam is a 48 m high concrete gravity dam. Located about 180 km southwest of Townsville (Australia), it is the largest dam in Queensland and one of the largest spillway capacities in Australia. Its catchment area is about 130,000 km². The reservoir, called Lake Dalrymple, has a storage capacity of 1860 Mm³. The spillway is 504 m wide, with an ungated ogee crest followed by a 49° smooth chute, ending with a flat ski jump equipped with 5.5 m high splitters, designed to ventilate the underside of the deflected nappe (Figure 1A).

Completed in 2011, the Hinze Dam Stage 3 is a 1.85 km long rockfill structure on the Nerang River. Located about 70 km south-south-east of Brisbane (Australia), its catchment area is about 207 km². The storage capacity of the reservoir is 311 Mm³. The dam is equipped with a 12.25 m wide primary spillway consisting of an ogee crest with small steps followed by a steep stepped chute and a hydraulic jump energy dissipator located about 35 m below the chute crest (Figure 1B).

The (original) third large dam was completed in 2005. It is located on the Burnett River (Australia), and its catchment area is 33,000 km². The primary spillway was 315 m wide, with an uncontrolled ogee crest followed by a 1V:0.64H steep stepped slope, ending with a hydraulic jump stilling basin acting as a plunge pool at design discharge (Figure 1C).

Additional observations were performed in a 1:15 scale three-dimensional physical model of the Hinze Dam primary spillway (Chanson & Hu, 2024). The spillway model was slightly modified and equipped with a simplified broad crest, followed by a downstream curve leading to two small steps, followed by the steep stepped chute $\theta = 51.3^\circ$ (1V:0.8H). The laboratory approach flow conditions were smooth and quiescent. The water was delivered into the 1.7 m deep and 5 m wide concrete basin through a 4.5 m long manifold style diffuser. The intake basin was equipped with baffles and three rows of flow straighteners, before a 2.8 m long smooth symmetrical convergent channel. The combination of a manifold style diffuser, baffles, flow straighteners and long concrete sidewalls converging at a ratio of 1:5.08, resulted in a smooth and waveless flow into the spillway crest (Zhang & Chanson, 2015; Chanson, 2025).

2.2. Field observations

Prototype observations were conducted by the second author at the three subject large dam spillways located in Australia between 2010 and 2025 (Table 1, Figure 1D).

At the Burdekin Falls Dam, the catchment received a catchment-wide average cumulative rainfall of 250 mm between 29 January and 12 February 2025. The rainfall runoff led to the third highest water level ever recorded in Lake Dalrymple, i.e. 6.725 m above full storage level (FSL) and a peak outflow of 18,600 m³ s⁻¹ (i.e. 36.9 m² s⁻¹). The dam continued to spill from February up to 14 August 2025, effectively spilling a volume of water equivalent to twice the total mean annual national water demand. Detailed observations of the spillway operation took place primarily on 4, 9 and 13 February during the February 2025 event.

Still photographs and movies from remotely piloted aircraft (i.e. aerial drones) were taken by Sunwater staff, which were later analysed by the authors. These delivered some unique insights into the basic free-surface flow features on the spillway, including the developing flow region, the onset of free-surface aeration, ski jump take-off and splitter operation, and large-scale free-surface turbulent structures during the large outflows.

The photographic and video observations were recorded with a dSLR PentaxTM K-3iii (Ricoh Imaging, Japan), a dSLR PentaxTM K-3 (Ricoh Imaging, Japan), and a dSLR PentaxTM K-7 (Ricoh Imaging, Japan), equipped with professional grade dSLR lenses. Additional photos and video were obtained using an AppleTM iPhone XI (Apple Inc., USA), a PanasonicTM Lumix DMC-FZ20 camera (Panasonic Holdings Corporation, Japan), CasioTM Exilim EX-10 camera (Casio Computer Co. Ltd, Japan), and a few point-and-shoot digital cameras, by the second author. Reliable quantitative observations were derived from the high-quality photographic and movie records, tied to precisely located ground reference points, landmarks and cross-sectional transects.

3. Developing flow region of spillway chutes

3.1. Water surface scars and striations

At all structures, the water surface in the upstream reservoir was calm and the surface velocities were small, with the runoff smoothly converging towards the ungated spillway. At Burdekin Falls Dam and the third large dam, land-based and aerial imagery typically showed large floating debris streaks slowly advancing towards the spillway near the centre of the reservoir outflow channel. At all three subject dams, the water colour was dark brown, indicating some suspended sediments in the water column. The flow at the ungated ogee crest was critical, and the spillway crest acted as a hydraulic control. On the spillway chute, the flow accelerated, and the water surface became progressively choppy, before becoming self-aerated.

In the developing non-aerated flow region, the free surface presented thin longitudinal surface striations, illustrated in Figures 1C, 2A, 2B. The free-surface



Figure 2. Longitudinal free-surface striations and surface scars in prototype chute spillways with uncontrolled crest during large flood events (Photographs Hubert Chanson). (A) Surface striations (light blue arrows) immediately downstream of the crest at Burdekin Falls Dam spillway (North Queensland, Australia) – $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, shutter speed: $1/8000 \text{ s}$, aperture f2.4, 13 February 2025 – flow direction from right to bottom left. (B) Surface striations (red arrows) at Hinze Dam spillway (south-east Queensland, Australia) – $Q = 116 \text{ m}^3 \text{ s}^{-1}$, $Re = 4.2 \times 10^7$, shutter speed: $1/200 \text{ s}$, aperture f5.6, 27 February 2022 – flow direction from top left to bottom right.

striations developed above the crest, continuing until the inception of free-surface aeration. With increasing downstream distance, they became rougher with a ‘whitish’ colour depending upon the lighting conditions

(Figure 2B). It was suggested (Binnie, 1967) that these surface striations originated in a surface-tension effect. Such streamwise surface striations were observed at the Burdekin Falls Dam, Hinze Dam and third large

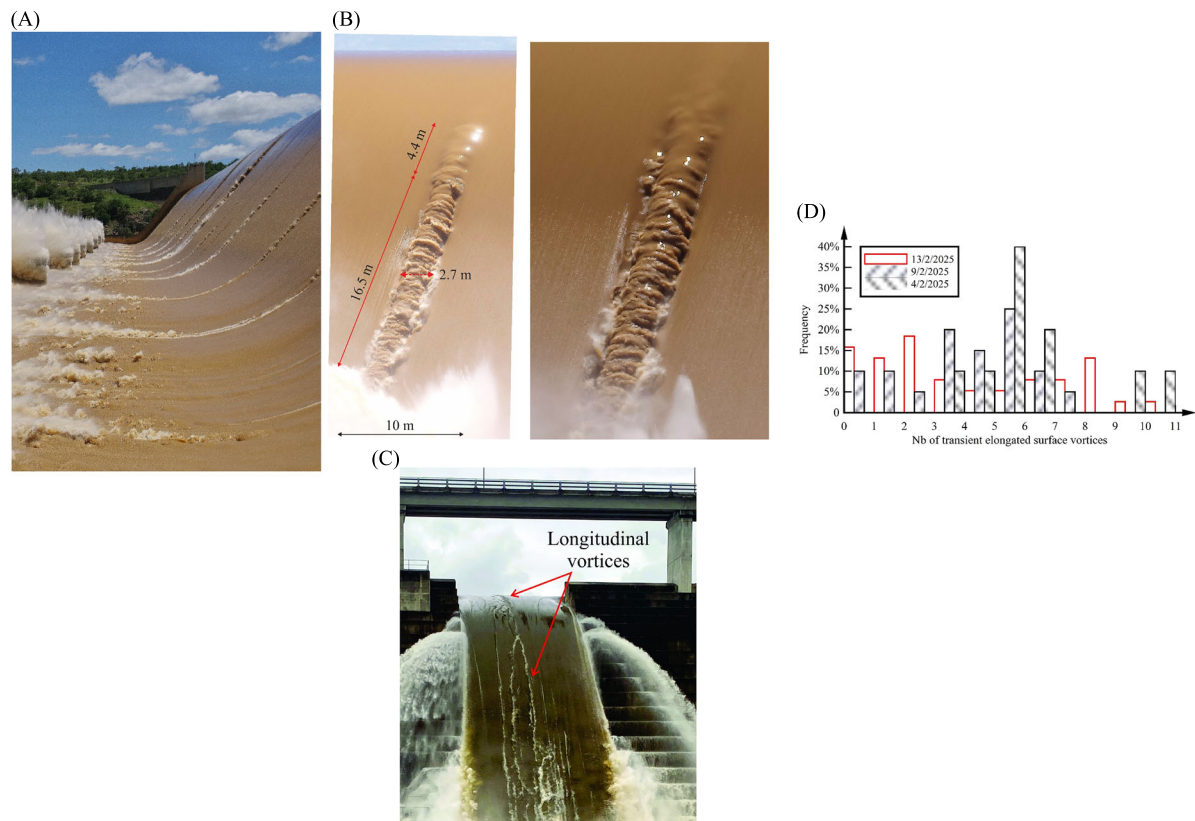


Figure 3. Elongated transient surface vortices at prototype chute spillways with uncontrolled crest during large flood events (Photographs Hubert Chanson). (A) Photograph of eight simultaneous parallel transient vortices at Burdekin Falls Dam (North Queensland, Australia) – $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, shutter speed: $1/8000 \text{ s}$, aperture $f2.4$, 13 February 2025. (B) Details of elongated transient surface vortices at Burdekin Falls Dam spillway (North Queensland, Australia) – $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, shutter speed: $1/250 \text{ s}$ and $1/1000 \text{ s}$, aperture $f6.3$, 13 February 2025 – flow direction from top right to bottom left. (C) Hinze Dam spillway (south-east Queensland, Australia) – $Q = 273 \text{ m}^3 \text{ s}^{-1}$, $Re = 8.9 \times 10^7$, shutter speed: $1/2625 \text{ s}$, aperture $f1.8$, 10 March 2025. (D) Histogram of number of transient elongated longitudinal surface vortices observed across the 504 m wide Burdekin Falls Dam spillway (North Queensland, Australia).

dam spillways, and also at the Trevallyn Dam spillway (Australia) during major floods by the second author, and in the UQ spillway model. The surface striations do not appear to be Reynolds number related, at least for $Re > 10^5$. A photograph of surface striations at the Hinze Dam spillway is presented in Figure 2B. Some streamwise surface striations at the third large dam spillway may be seen in Figure 1C. The striations were small and they neither disturbed the flow conditions at the spillway crest nor the discharge rating curve.

3.2. Large elongated vortices/streaks

Large transient elongated surface vortices were observed along the chute upstream of the inception region at all large dam spillways (Figures 1C, 3A, 3B, 3C). These short-lived highly energetic longitudinal features were transient phenomena, lasting a few minutes before disappearing.

At Burdekin Falls Dam spillway, they were spaced transversely every 20 m to 100 m across the 504 m wide chute. These transient elongated surface vortices were sometimes but not always aligned with monolith joints

and major longitudinal cracks, suggesting that they might be exacerbated by construction irregularities. Figure 3A illustrates eight simultaneous parallel transient vortices and there were up to 11 such structures observed at some times (Figure 3D). Figure 3D presents the histogram of the frequency of different numbers of instantaneous elongated vortices during three observation periods across three different days. The data suggested (a) a wide range of instantaneous number of large elongated longitudinal surface vortices, from zero (none) to more than 10, (b) relatively flat histograms, except possibly on the 4 February 2025, and (c) relatively similar results for the three different flow conditions.

These large elongated structures were believed to be caused by the upwelling of three-dimensional under-water currents in the reservoir, flowing upwards along the upstream face of the dam wall and interacting with the spillway overflow free surface, as sketched in Figure 4. These would somehow resemble the vortex filament induced by secondary motion shown by Rouse (1938). Similar free-surface streaks were shown by Levi (1965, 1967) during a major overflow at Miguel Hidalgo ‘El Mahone’ Dam spillway (Mexico) and by Anwar

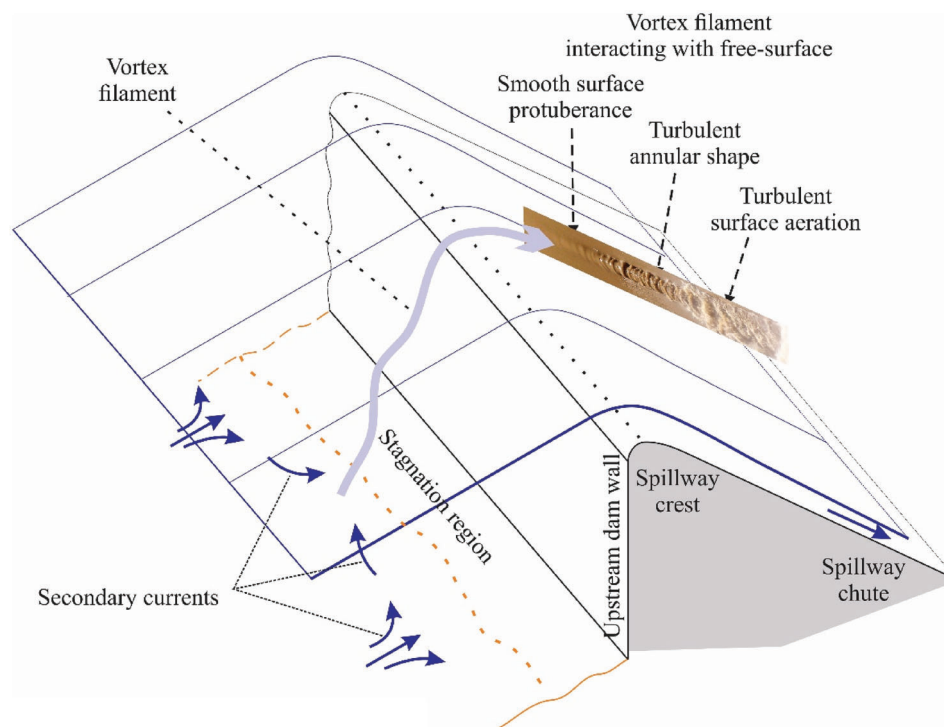


Figure 4. Upwelling of three-dimensional underwater currents in the reservoir, rising along the upstream dam wall and leading to the development of transient elongated vortices on the spillway chute.

(1994) over a weir, both with uncontrolled crest overflows. At Burdekin Falls Dam, turbidity currents were documented in Lake Dalrymple, upstream of the dam wall (Faithful & Griffiths, 2000; Cooper et al., 2017). While not conclusive, the three-dimensional underwater currents might have been some form of dense turbidity currents.

Visually, the transient elongated structures developed at the upstream end with a smooth elongated surface bump of the water surface, as seen in Figure 3B, downstream of the spillway crest. The structures rapidly expanded with a turbulent, annular, broken shape, presenting some air–water aeration towards the downstream end (Figure 3B). At Burdekin Falls Dam, a fully-developed elongated surface structure could be up to 5 m wide and 25 m long, although the majority were 1–2 m wide, and 10–20 m long. Similar streamwise surface streaks were also observed in the UQ spillway model (Figure 5). While such features are rarely seen in the laboratory, a key feature of this facility was the very smooth and quiescent approach flow conditions, owing to a 1.7 m deep and 5 m wide concrete basin, equipped with a 4.5 m long manifold style diffuser, followed by baffles and flow straighteners.

The flow conditions for which these transient elongated structures were recorded are summarized in Table 2 at all subject dam spillways. Overall, these short-lived elongated surface vortices were seen for overflow

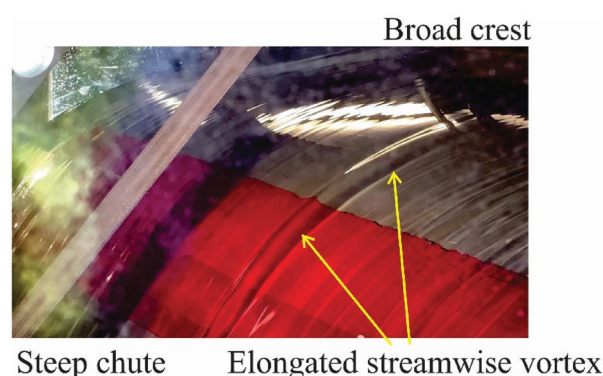


Figure 5. Elongated transient surface vortices at model chute spillways with uncontrolled crest (Photograph Hubert Chanson) – $Q = 0.185 \text{ m}^3 \text{ s}^{-1}$, $\text{Re} = 7.4 \times 10^5$ – flow direction from right to bottom left.

conditions fulfilling:

$$0.135 < \frac{H_1}{\Delta z_o} < 0.18$$

Occurrence of elongated surface vortices (1)

where H_1 is the upstream head above crest and Δz_o is the spillway crest height above the reservoir. It should be noted that Equation (1) was developed based upon prototype data with an upstream vertical wall (Table 2). While Equation (1) corresponds to a narrow range of flow conditions, it is based upon prototype and laboratory observations conducted across a much wider range of discharges.

These transient longitudinal vortices are not unique to ungated spillways, as similar behaviour has been

Table 2. Flow conditions corresponding to the observations of large transient longitudinal surface vortices/streaks in spillway chutes.

Dam spillway	Δz_0 (m)	H_1/Dz_0	Re	Date of overflow
Burdekin Falls Dam	33.7	0.14	7.9×10^7	4 February 2025
		0.18	1.2×10^8	9 February 2025
		0.17	1.1×10^8	13 February 2025
Hinze Dam	34.5	0.167	1.1×10^8	31 March 2017
		0.147	8.9×10^7	10 March 2025
		0.135	7.1×10^7	30 December 2010
UQ 1:15 model of Hinze Dam spillway	1.4	0.14–0.165	5.5×10^5 – 7.5×10^5	November 2025

Notes: Δz_0 : spillway crest height above the reservoir; H_1 : head above crest; Re: Reynolds number defined in terms of the equivalent pipe diameter.

reported in the non-aerated flow region of gated chute spillways, e.g. at Aviemore Dam and at Canyon Ferry Dam (Cain, 1978; Falvey, 1980).

4. Inception of free-surface aeration

The inception of free-surface aeration is a complicated interfacial process (Hino, 1961; Toro et al., 2017). In chute spillway flows, the upstream region is typically non-aerated and strong air–water mixing occurs when the turbulent shear stress in the water phase next to the free surface exceeds the combined effect of gravity and surface tension (Ervine & Falvey, 1987; Chanson, 1997, 2009). At the upstream end of the spillway, the flow is rapidly accelerated, and a turbulent boundary layer develops along the channel invert. On steep spillway chutes, like Burdekin Falls Dam, Hinze Dam and the third large dam, the inception of air entrainment starts when the outer edge of this developing turbulent boundary layer begins interacting with the water surface (Halbronn, 1952; Wood et al., 1983; Wood, 1985). These interactions are energetic with strong air–water ejections, and the position of the onset of free-surface aeration is constantly fluctuating about a mean position.

Immediately upstream of the inception region, large-scale surface turbulence was seen in the form of well-marked large boils and explosive ‘puffs’ of air at all subject large dams (Figure 6). At Burdekin Falls Dam, the growth of the elongated transient surface vortices tended to contribute to some aeration of the whole free surface. Photographic details of the inception region are seen in Figures 3A, 6A and 6B at Burdekin Falls during a large overflow with $Re = 1.1 \times 10^8$, and in Figures 1B and 3B at Hinze Dam.

In the inception region of free-surface aeration, the air–water surface features presented a variety of elongated air–water shapes with an aspect ratio (length to width) generally larger than 5 to 10. The observations at Burdekin Falls Dam, Hinze Dam and the third large dam were consistent with previous observations at Somerset and Wivenhoe Dams (Chanson, 2022, 2024), at Pedrogao Dam (Matos & Meireles, 2014) and at Aviemore Dam (Keller, 1972; Cain, 1978) where

ratios greater than 2 to 5 were seen. We are fairly confident about the quality of the prototype observations for the three subject dams, i.e. Burdekin Falls Dam, Hinze Dam, and the third large dam, as well as those seen at Aviemore Dam during a visit by the second author. We acknowledge that the prototype observations at Somerset, Wivenhoe and Pedrogao Dams might have more uncertainty. In contrast, laboratory observations reported average ratios close to unity (Chanson, 2024), although the indoor laboratory observations might be affected by poorer lighting conditions. The differences between prototype and model observations indicate that the model results in self-aerated flows might not be fully extrapolated to full-scale prototype spillways operating at extraordinary high Reynolds numbers without certain limitations and potential scale effects, as previously discussed (Wood, 1985; Chanson, 2013; Zhang & Chanson, 2017).

The average location of the inception region is a fundamental parameter that serves as a boundary condition for modelling the gradually-varied air–water flow region (Wood et al., 1983; Wood, 1991; Chanson, 1993; Matos, 2000). Figure 7 summarizes the dimensionless averaged location of the inception region L_I/d_c at all three large dams during large floods as a function of the Reynolds number Re , where L_I is measured from the spillway crest along the chute profile and d_c is the critical flow depth. The recent observation at Burdekin Falls Dam is compared to the stepped chute observations at Hinze Dam and the third large dam, and smooth chute data at Chinchilla Weir (Australia) and Aviemore Dam (New Zealand) in Figure 7. All the data are plotted together against the empirical correlation:

$$\frac{L_I}{d_c} = 10 + \frac{4.65 \times 10^5}{Re^{0.7}} \quad \text{Inception of free-surface aeration} \quad (2)$$

Some agreement in trend is seen between prototype spillway data and Equation (2) (Figure 7). Altogether, the prototype data suggested, in first approximation, an asymptotic limit for extraordinary high Reynolds numbers:

$$\frac{L_I}{d_c} \sim 10 \text{ for } Re > 10^8 \quad (3)$$

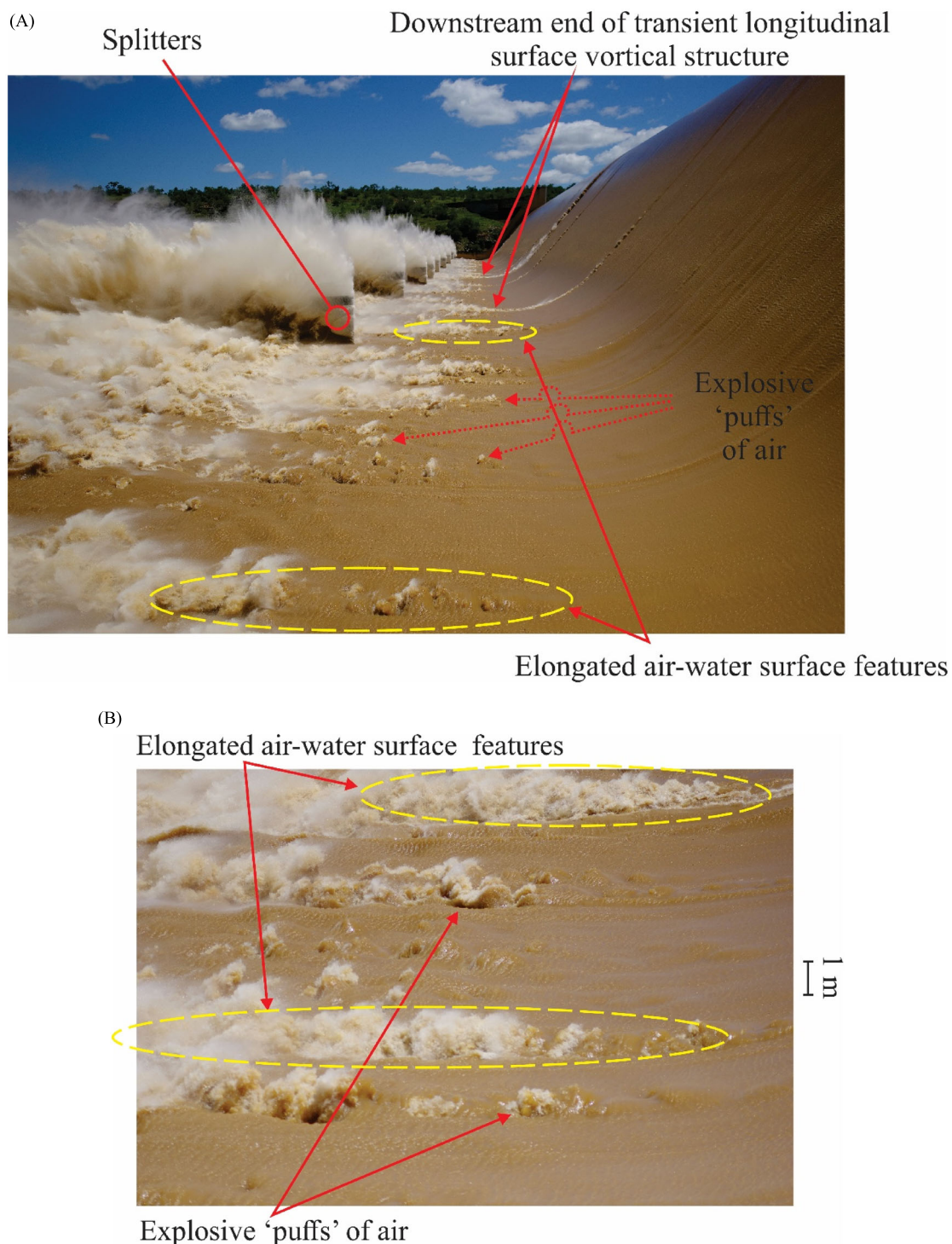


Figure 6. Air–water surface features in the inception region of free-surface aeration during the smooth chute spillway operation at the Burdekin Falls Dam spillway (North Queensland) (Photographs Hubert Chanson) – $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, 13 February 2025. (A) Sideview from above – shutter speed: $1/8000 \text{ s}$, aperture f2.4. (B) Close-up photograph (with macro lens) – shutter speed: $1/8000 \text{ s}$, aperture f2.8.

although the trend would need to be confirmed by new prototype observations to be recorded at Reynolds numbers in excess of 1.5×10^8 .

5. Air–water flow

Downstream of the inception region of free-surface aeration, the air–water flow presented a white appearance, highlighting self-aeration and air entrainment.

The free-surface aeration was uncontrolled. At all the large dams and for all observed flood conditions, the self-aerated flows presented a complicated mix of air and water with an intricate inner structure (Chanson, 1997, 2009; Brocchini & Peregrine, 2001; Brocchini, 2002). At least two typologies were observed in the form of interfacial self-aeration above the spillway chute, and impingement aeration in the stilling system and at splitters.

	Dam spillway	Reference(s)
Smooth chutes	Burdekin Falls (Australia)	Present study
	Chinchilla Weir (Australia)	Chanson & Apelt (2023), Chanson (2025b,2026)
	Aviemore Dam (New Zealand)	Cain (1878)
Stepped chutes	Hinze Dam	Chanson (2022), Present study
	Third large dam	Chanson et al. (2015)

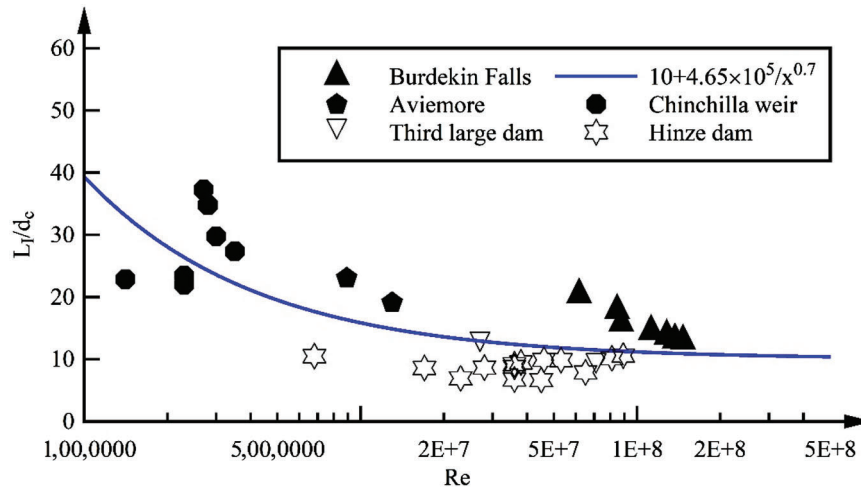


Figure 7. Dimensionless streamwise location L_l/d_c of the inception region of free-surface aeration at large dam spillways during large flood overflows with extraordinary high Reynolds numbers – comparison with Equation (2).

At Burdekin Falls, the main types of air–water flows were: (1) self-aeration on the spillway chute, (2) interfacial aeration along the deflected jet downstream of the ski jump, and (3) impingement on the splitters with intense spray in the wake, excluding the deflected jet impact onto the downstream river channel. All these air–water flows are illustrated in Figures 1A, 3B and 6. Downstream of the ski jump, the upper free surface was characterized by air–water surface waves, seen downstream of splitters and in the deflected nappe, similar to those reported at Three Gorges Dam (China) and theoretically analysed by Toombes and Chanson (2007). Further, a strong mist was generated by both free-jet nappe impact and by the splitters, rising upwards 5 m to 10 m above the top of the 5.5 m high splitters. The mist reached some observation points located over 500 m away downstream of the chute toe. Some similar spray and mist were seen and documented at the Hinze Dam and the third large dam.

At the Hinze Dam, the free-surface aeration was intense above the stepped chute for low to medium discharges, when the inception region occurred upstream of the chute toe. Further, the chute flow impact on the baffle blocks was extremely turbulent and associated with a strong wavy motion above the blocks. The free surface above the stilling basin presented a chaotic appearance with air–water packets, reaching instantaneous vertical heights in excess of 9 m above the top of baffle blocks on 10 March 2025 (Figure 1B), consistent

with prototype observations ‘even up to 10 m in height’ reported by Jevdjovich and Levin (1953).

At the third large dam, the high-velocity chute flow plunged into the hydraulic jump stilling basin. The air–water flow in the stilling basin was turbulent and three-dimensional. Unsteady surface waves were seen across the entire stilling basin breadth.

All the prototype spillway observations reported a significant suspended sediment load in the overflow, implying a three-phase flow spillway operation with air, water and sediments, not including floating debris. In such three-phase flows, the presence of fine solid particles increases the difficulties of hydraulic modelling because the turbulent modulation in sediment-laden flows cannot be neglected, and physical measurements in the three-phase flow are nearly impossible (Jha & Bombardelli, 2009; Chanson, 2013).

5.1. Air–water surface waves

At all three subject dams, large air–water surface waves were observed at the downstream end of the spillway chutes. Two main types of air–water surface waves were seen: impact waves caused by the impingement of the high-velocity chute flow on obstacles (i.e. baffle blocks, splitters), and air–water surface waves in air–water jet.

Some stagnation shocks were observed at the impact of the high-velocity chute flow on the upstream end

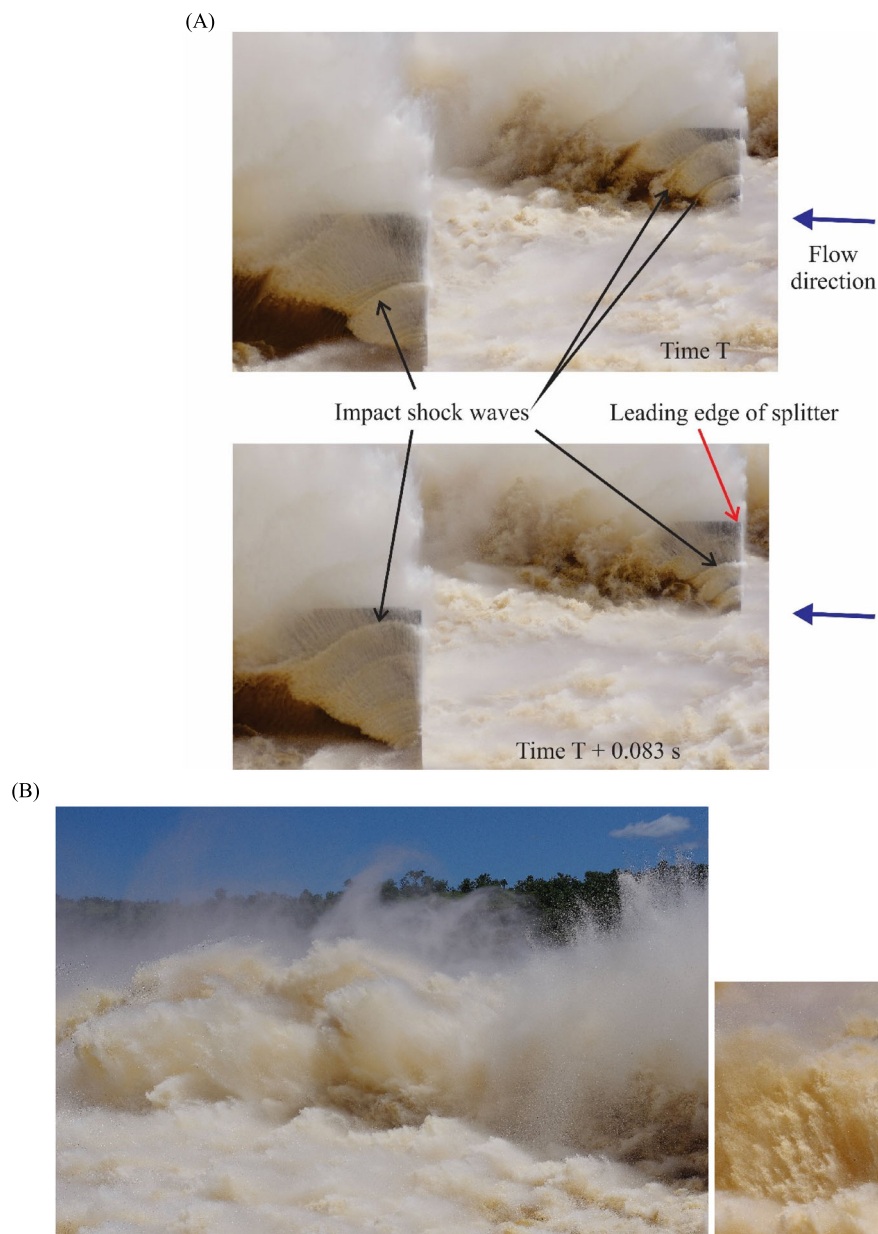


Figure 8. Air–water surface waves in large dam spillways during large floods. (A) Details of impact shock waves at the splitters at Burdekin Falls spillway (North Queensland) (photographs Hubert Chanson) – flow direction from right to left, $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, 13 February 2025 – burst of two photographs with shutter speed: $1/8000 \text{ s}$, aperture f3.5. (B) Air water interfacial waves in the deflected nappe downstream of splitters at Burdekin Falls spillway (North Queensland) (Photographs Hubert Chanson) – flow direction from right to left, $Q = 13,700 \text{ m}^3 \text{ s}^{-1}$, $Re = 1.1 \times 10^8$, 13 February 2025 – shutter speed: $1/8000 \text{ s}$, aperture f5. Inset: details of air–water wave structure.

of the splitters at Burdekin Falls Dam (Figure 8A). The air–water impact waves propagated along the side-walls of the splitters, with Figure 8A showing two high-shutter speed photographs taken 0.83 s apart. The dimensionless generation frequency, i.e. Strouhal number, of these shock waves was about $F \times d/V \approx 0.4$, with F the frequency (in Hz), d and V respectively being the flow depth and velocity at impact, while the dimensionless wave length L_w/d ranged between 2 and 3. Downstream of the splitters, the deflected jet presented air–water surface waves, similar to those seen in deflected jets at the Three Gorges Project Dam (China) and Wivenhoe Dam (Australia) by the second author,

and at Morrow Point Dam (USA) shown in Ervine and Falvey (1987).

At the Hinze Dam spillway, air–water surface waves were seen above the baffle blocks at extraordinary high Reynolds number flow conditions (Figure 1B). Their dimensionless ejection frequency was about $0.045 < F \times d/V < 0.05$, while the surface wave height above the downstream water level was $9 < H_w/d < 10.7$. The dimensionless surface wave heights were significantly larger than physical data obtained in hydraulic jumps without baffle blocks (e.g. Mouazé et al., 2005; Chachereau & Chanson, 2011). More details are reported in Appendix A.

6. Conclusion

During major floods, large dam spillways can experience high-velocity free-surface flows with extraordinary high Reynolds number ($Re > 10^8$). In such high Reynolds number flows, the turbulent multiphase processes are complex, and a number of theoretical considerations have not been validated. Qualitative and quantitative observations were recorded at three large dams during large overflows associated with extraordinary high Reynolds number flow conditions: Burdekin Falls Dam in north Queensland, Hinze Dam in south-east Queensland, and the third large dam in Central Queensland, Australia. All the spillways were un-gated, equipped with an ogee crest, and followed by a steep chute. The field observations were conducted between 2010 and 2025, and complemented by additional prototype observations and some large-size physical modelling, albeit limited. At the Burdekin Falls Dam, Hinze Dam and the third large dam, the observed flood conditions corresponded to discharges less than 20% of the design flood event, and less than 10% of the latest probable maximum flood (PMF) estimates.

For all dam spillways, the reservoir inflow was smooth and waveless. The flow was accelerated above the spillway crest, and self-aeration took place once the outer edge of the developing boundary layer started to interact with the free surface. For a range of flow conditions described by Equation (1), large transient elongated turbulent vortices were seen at the free surface in the non-aerated flow region. They were attributed to the interactions of underwater currents originating from the reservoir and forming vortex filaments advected upwards along the vertical face of the dam before interacting with the free surface of the accelerating chute flow. The inception of free-surface aeration took place within an energetic region characterized by well-marked large surface scars, boils, and explosive ‘puffs’ of air. The average location of the inception region was correlated by Equation (2), with possibly a lower limit L_I/d_c about 10 for extraordinary high Reynolds numbers (i.e. $Re > 10^8$). Downstream of the inception region, the self-aerated flows presented a mix of air and water with an intricate inner structure. Large air–water surface waves were observed in the energy dissipation structure. Further, all the prototype observations indicated sediment-laden inflows, implying a three-phase flow operation with air, water and sediments flowing within the spillway.

While the present observations of air–water flow features were consistent with previous anecdotal observations at dam spillways, a key aspect was the detailed and systematic observations at all three structures during large overflow events at extraordinary high Reynolds numbers. These included static and aerial observations at Burdekin Falls in February 2025, systematic photographic and cinematographic records at Hinze Dam

between 2013 and 2025, and unique observations at the third large dam between 2010 and 2013 before its modification. In hydraulic engineering, a major challenge is the extrapolation of the results to full-scale prototype operations during major flood events. The present work provides exceptional data and imagery related to large dam spillway hydraulics and air–water flows at extraordinary high Reynolds numbers.

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Author contributions

CRedit: **Carlos Gonzalez:** Data curation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing; **Hubert Chanson:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing

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Notation

A	cross-section area (m^2)
D_H	equivalent pipe diameter (m): $D_H = 4 \times A/P_w$
d	water depth (m)
d_c	critical flow depth (m)
d_c	critical depth (m): $d_c = \sqrt[3]{\frac{q^2}{g}}$
F	frequency (Hz)
g	gravity acceleration: $g = 9.80 \text{ m s}^{-2}$ in Queensland, Australia
H_w	air–water surface wave height (m)
L_I	longitudinal distance of the inception region of free-surface aeration (m)
L_w	air–water surface wave length (m)
P_w	wetted perimeter (m)
Q	water discharge ($m^3 \text{ s}^{-1}$)
q	unit discharge ($m^2 \text{ s}^{-1}$)
Re	Reynolds number defined in terms of the mean velocity and hydraulic diameter (–): $Re = \rho \times V \times D_H / \mu$
St	dimensionless frequency, i.e. Strouhal number, defined as (–): $St = \frac{F \times d}{V}$

V	cross-sectional averaged velocity (m s^{-1})
V_c	critical flow velocity (m s^{-1})
μ	dynamic viscosity of water (Pa s)
ρ	water density (kg m^{-3})
c	critical flow conditions

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Appendix A: Characteristics of air–water surface waves in large dam spillways during large floods

At all three subject dams, large air–water surface waves were observed at the downstream end of the spillway chutes.

The prototype observations are summarized in Figure A1, where they are compared to a number of relevant prototype and laboratory data.

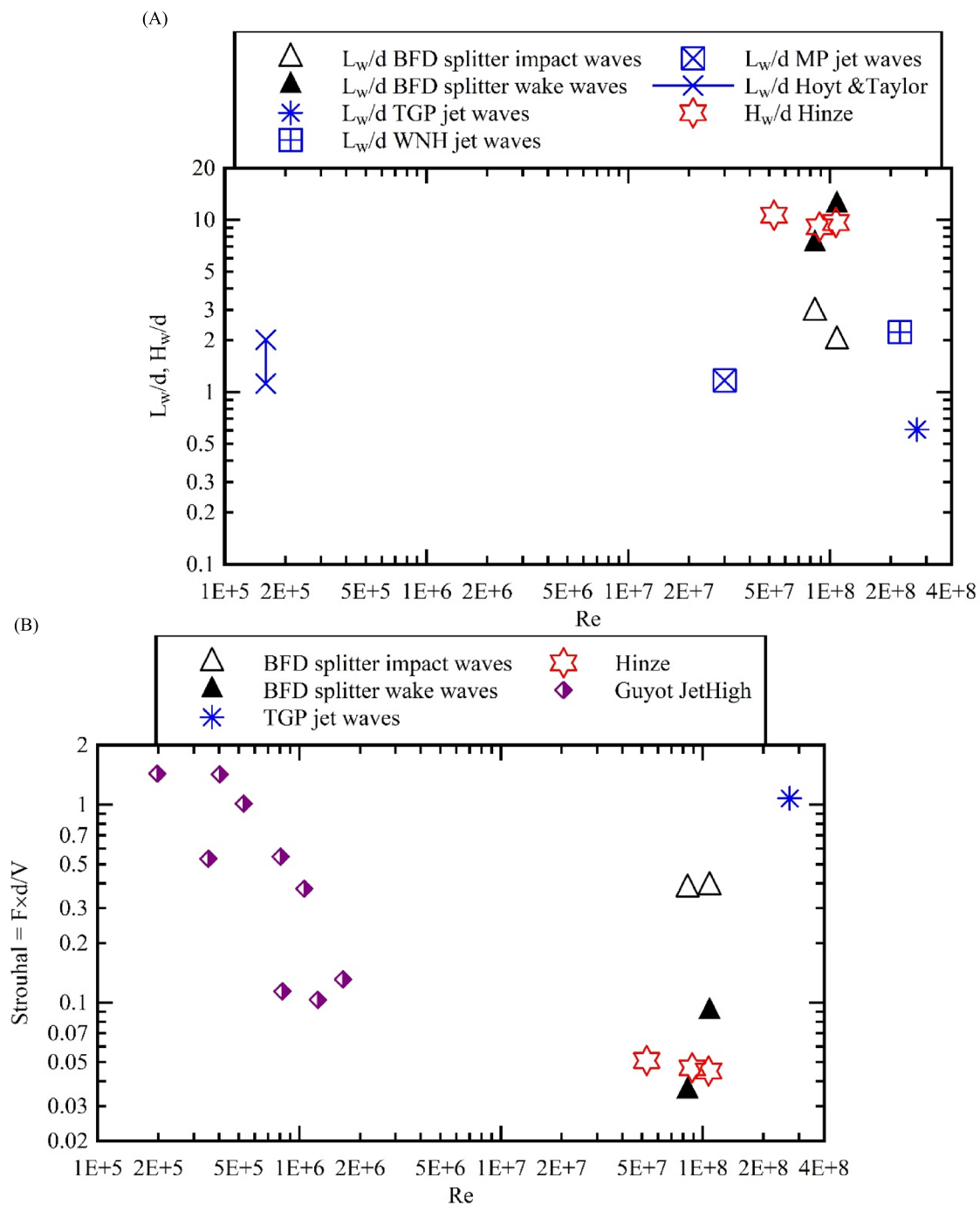


Figure A1. Characteristics of air–water surface waves in large dam spillways during large floods (A) Air–water surface wave lengths L_w/d at Burdekin Falls Dam (BFD), Three Gorges Project (TGP), Wivenhoe Dam (WNH) (Data H. Chanson) and Morrow Point Dam (MP) (Ervine & Falvey, 1987) – comparison with surface wave height data H_w/d at Hinze Dam (Hinze) (Data H. Chanson) and surface wave length data L_w/d of Hoyt and Taylor (1977) (Hoyt & Taylor). (B) Air–water surface wave frequency $F \times d/V$ at Burdekin Falls Dam (BFD), Three Gorges Project (TGP) and Hinze Dam (Hinze) (Data H. Chanson) – comparison with physical data by Guyot (2019) (JetHigh).