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BUBBLES, TRANSIENT TURBULENCE AND FISH - CHALLENGING HYDRAULIC STRUCTURES OF THE 21ST CENTURY

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ABSTRACT

A hydraulic structure is a man-made system interacting with the rainfall runoff to store or convey water. Current designs tend to be conservative not differing much from ancient designs. Modern hydraulic structures are often designed based upon simplistic steady flow concepts to optimise their performances. Today hydraulic engineers must embrace new challenges, as water plays a key role in human perception and is indispensable to all forms of life. In this invited plenary keynote, the writers review these challenges in terms of self-aeration processes at hydraulic structures, transient turbulence generated in conveyance structures during surge events, and upstream fish passage in box culverts. It is argued that a number of technical solutions are not satisfactory, e.g. in terms of aquatic fauna, fluid-structure interactions and operational restrictions. Altogether, the technical challenges in hydraulic structure design are gigantic for the 21st century hydraulic engineers. The future lies in strong links between engineering innovation, excellence in hydraulic research and quality education in universities, complemented by indispensable interactions between engineering and other disciplines.

Keywords: Hydraulic structures; Air bubble entrainment; Unsteady transient surges; Upstream fish passage; road crossings; Challenges; Hydraulic designs.

1 INTRODUCTION

A hydraulic structure is a man-made system which interacts with the rainfall runoff, to store or convey water. Examples include a dam and its spillway (Fig. 1A), a water canal with its control gates (Fig. 1B) and a culvert beneath a road (Fig. 1C). The construction of hydraulic structures is one of the oldest civil engineering activities, because the human life is totally dependent upon drinking water supply (Smith 1971, Schnitter 1994). Although the oldest hydraulic structure remains unknown, world-famous engineering heritage structures include the Assyrian water supply of Nineveh, the Roman aqueducts, the large sewer systems of European and North-American cities, and the thin concrete arch dams in rural Australia. Traditionally, two key requirements of civilisations have been the storage and transport of water, particularly for irrigation demands arising from the development of intensive agriculture, drinking water supply, public health and sanitary requirements of large cities. Basic hydraulic engineering calculations rely upon fundamental hydrodynamics and theoretical studies with a range of trusted and proven solutions. Although hydraulic engineers were at the forefront of science for centuries, current designs tend to be conservative, in light of the knowledge available at the time, and might not be conservative according to current findings, while they differ barely from ancient designs (Chanson 2007,2008). Modern hydraulic structures are typically designed based upon steady flow concepts to optimise the cross-sectional shape of a canal, the discharge capacity of a spillway crest, the energy dissipation performances of a stilling basin, and the size of culvert barrel.

In 2019, hydraulic engineers must embrace new challenges, as water plays a key role in human perception and it is indispensable to all forms of life. In dam engineering, the continuous re-evaluation of spillway discharge capacity leads to much needed novel spillway (re-)designs, in particular in geographical regions of extreme hydrology and limited rainfall and runoff data. Major advances in two-phase flows in mechanical and nuclear engineering have brought up new forms of multiphase gas-liquid and liquid-solid models, that could be embedded in hydraulic structure design (Jhia and Bombardelli 2009, Chanson 2013, Bung and Valero 2016). The interaction between hydraulic structures and aquatic flora and fauna is a further complicated challenge (Kemp 2012, Nepf 2012, Maddock et al. 2013). Physical modelling exempted from scale effects is often impossible unless at full-scale, while some aquatic life might adapt their swimming pattern in man-made structures to maximize their efficiency (Wang and Chanson 2018a). Reservoir siltation continues to be a recurrent issue worldwide, exacerbated by the reduction of freshwater resources and suitable dam sites (Chanson 2008).

In this invited keynote, the writers outline a number of key challenges for current and future hydraulic structures, for which a combination of innovative engineering, research excellence and broad-based expertise is required. These encompass self-aeration in hydraulic structures, transient turbulence in conveyance structures, and the blockage to upstream fish passage caused by road crossings.

Figure 1. Challenges in hydraulic structure design. (A) Self-aeration at the Hinze dam spillway on 31 March 2017 ($d_c/h = 3.55$, $Re = 1.1\times10^8$); (B) Transient positive surge propagating in the Oraison hydropower canal following a rapid stoppage ($Q = 210$ m^3/s, $Re \sim 10^7$) (Photo I.G.N. in Cunge 1966); (C) Standard box culvert operation on Cubberla Creek on 4 June 2016, with a hydraulic jump in the inlet (Courtesy of Stewart Matthews)

2 FREE-SURFACE SELF-AERATION AT HYDRAULIC STRUCTURES

At a hydraulic structure, the interactions between the high-velocity turbulent water flow and the atmosphere may yield significant air entrainment associated with strong interactions between entrained bubbles and coherent structures (Rao and Kobus 1974, Wood 1991) (Fig. 1A & 1C). Traditionally, air entrainment in free-surface flow has been classified into singular aeration and interfacial aeration (Wood 1991, Chanson 1997,2009). Recent experimental observations suggested that the simplification masks a number of physical processes. In stationary hydraulic jumps, detailed air-water flow measurements showed that the air entrapment at the roller toe accounted for only one third of the total air entrainment in the roller, with extensive aeration along the upper surface of the breaking roller (Wang and Chanson 2015) (Fig. 2). In free-surface flows down spillways, the air-water exchanges in the upper flow region consist of a combination of interfacial aeration, air advection in surface waves, and ejected droplet impinging into the air-water mixture, with singular bubble entrainment at the drop impacts (Ervine and Falvey 1987, Chanson and Carosi 2007, Toombes and Chanson 2008) (Fig. 3). The flow down a spillway and in a water jet is further complicated by the interactions with the atmospheric boundary conditions.

The inception of air bubble entrainment is linked to a threshold level of tangential Reynolds stresses next to the free-surface (Chanson 2009,2013). Air entrainment occurs when the turbulent shear stress next to the air-water interface is large enough to overcome the surface tension (Ervine and Falvey 1987, Chanson 2009):

$$\frac{|vv|}{V^2} > \frac{\pi\,\sigma\,(r_1 + r_2)}{\rho_w\,A_{fs}\,V^2} \qquad [1]$$

where ρ_w is the water density, σ is the surface tension, V is the longitudinal water velocity, v is the instantaneous turbulent velocity fluctuation, r_1 and r_2 are the two principal radii of curvature of the free surface deformation, assuming an elongate spheroid, and A_{fs} is surface deformation area. For a spherical bubble of radius $r = r_1 = r_2$, and assuming isotropic turbulence, Equation (1) may be simplified into as

$$\frac{\mu_w\,V}{\sigma} > \sqrt{\frac{\mu_w{}^2}{2\,\rho_w\,\sigma\,\pi\,r\,\frac{|vv|}{V^2}}} \qquad [2]$$

for the onset of air bubble entrainment, with μ_w the water dynamic viscosity. Equation (2) is compared to experimental observations in Figure 4, predicting entrained bubble sizes within 0.2-100 mm at onset, for impact turbulence levels v_x'/V_1 between 1% and 15%. Despite the simplified development, Equation (2) predicts entrained bubble sizes comparable to physical observations at the onset of bubble entrainment in vertical plunging jets, as seen in Figure 4B. For these data (Cummings and Chanson 1999, Bertola et al. 2018), the inflow turbulence ranged from 2% to 5% in the physical experiments.

Once entrapped, the entrained air is convected within the water column as a result of the combined effects of turbulent diffusion and buoyancy. Various diffusion models were developed and applied successfully to a range of air-water flow typology and flow conditions (Wood 1984, Chanson 1997, Chanson and Toombes 2002). Recent analyses showed a marked decrease in the ratio D_t/ν_T of air bubble diffusivity to momentum exchange coefficient with increasing Reynolds number.(Chanson 1997). The finding might suggest some intrinsic limitation of laboratory investigations of air bubble diffusion process in self-aerated air-water flows and of their extrapolation to full-scale prototype applications (Zhang and Chanson 2017). In other words, an undistorted Froude similitude might be insufficient to describe accurately the air bubble diffusion process in self-aerated flows, since the ratio D_t/ν_T is consistently larger in laboratory models than in prototype data. Physical modelling of air-water flows in laboratory might overestimate the importance of the air bubble diffusion process in comparison to momentum exchanges and turbulent processes in large prototype hydraulic structures.

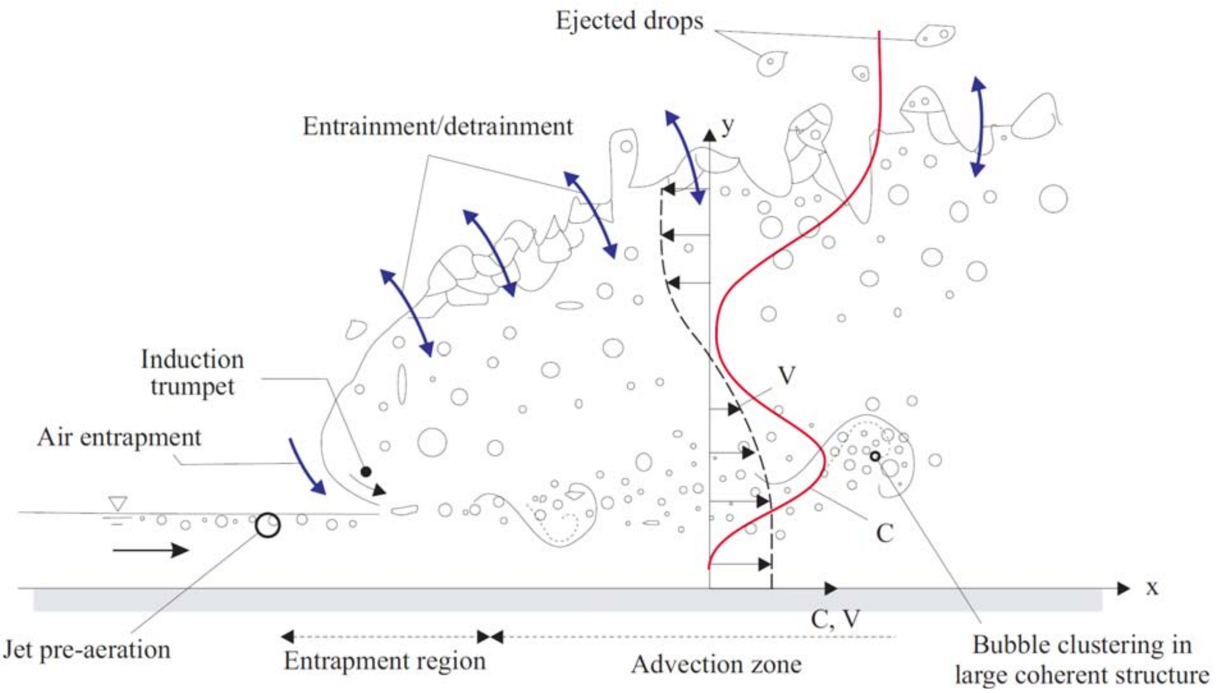

Figure 2. Air entrainment at a hydraulic jump with a breaking roller including seminal air-water features

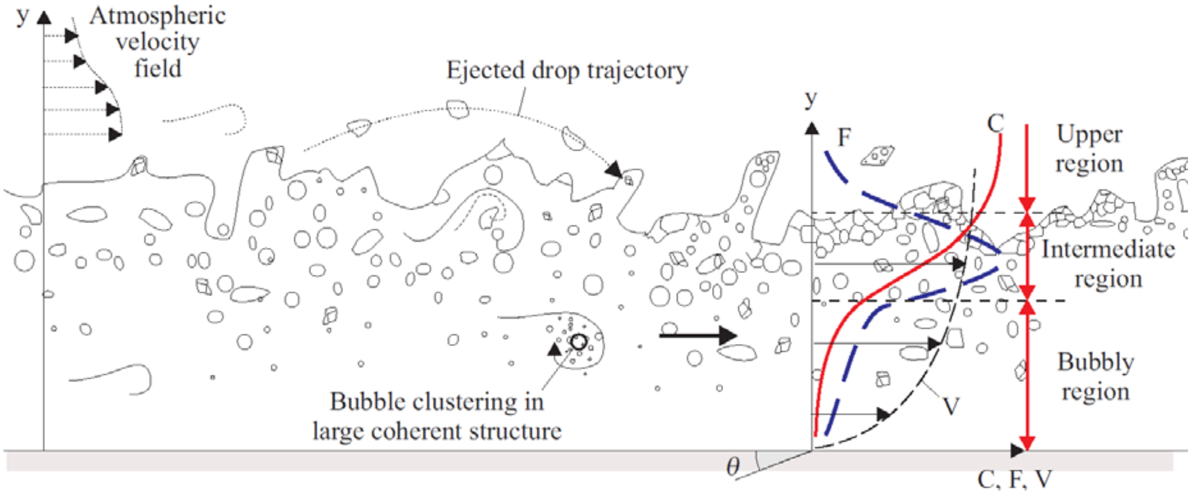

Figure 3. Free-surface-aeration down a supercritical spillway flow including seminal air-water flow features

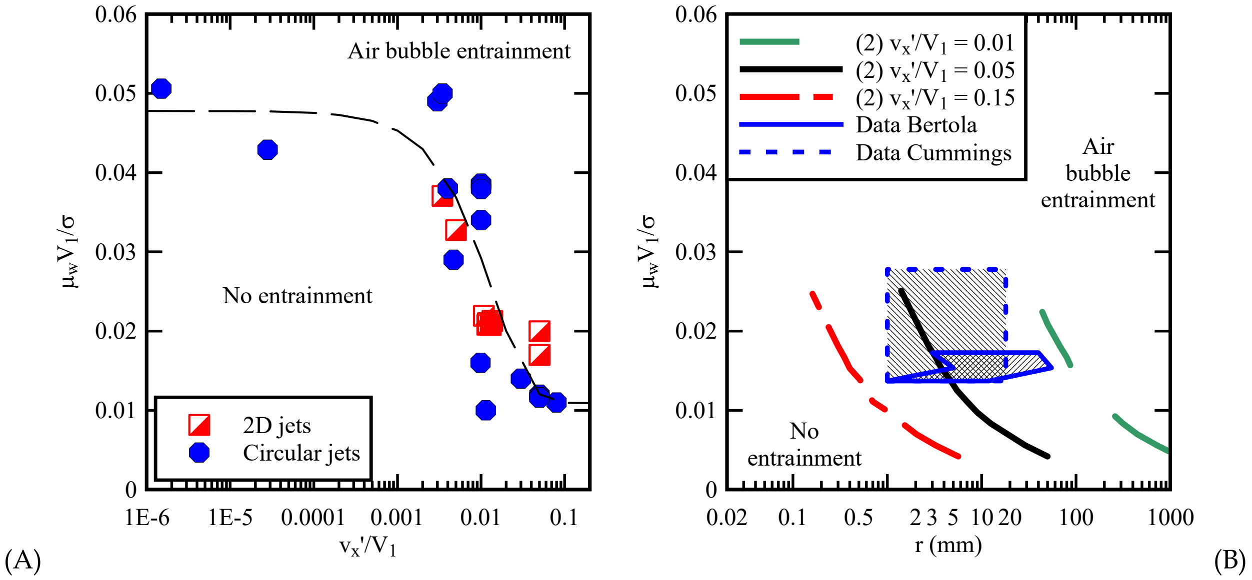

Figure 4. Onset of air bubble entrainment. (A) Vertical circular and two-dimensional plunging jets: dimensionless impact velocity V_1 as a function of the dimensionless normal stress v_xv_x of the impinging jet; (B) dimensionless impact velocity V_1 as a function of the entrained bubble size and impact turbulence level (Eq. (2))

3 UNSTEADY TRANSIENT TURBULENCE IN CONVEYANCE STRUCTURES

3.1 Presentation

In a conveyance structure, the brusque operation of control gates may induce large unsteady flow motion called surges, which might overtop the channel banks, damaging and eroding the channel (Favre 1935, Treske 1994). In a canal, a sudden increase in water depth is called a positive surge (Fig. 5A), while a rapid drop in water surface elevation is termed a negative surge (Fig. 5B). Visually, a positive surge appears very turbulent, either in the form of an undular bore (Fig. 1B) or a breaking bore (Fig. 5A), with a sharp discontinuity of the free-surface elevation. On the contrary, a negative surge appears to be a gentle drawdown of the water surface, sometimes barely perceptible by observers standing on the side (Fig. 5B).

In a canal, a surge is typically generated by some regulation gate operation. Free-surface measurements in large-size laboratory canals highlighted the rapid deformation of the free-surface in the immediate vicinity of the gate during the positive/negative surge generation process (Lubin et al. 2010, Sun et al. 2016). Instantaneous velocity measurements further indicated significant variations in longitudinal velocity during the positive/negative surge generation, as well as large fluctuations in all velocity components during the surge passage further upstream. The large instantaneous velocity fluctuations were associated with large Reynolds stress magnitudes. With both positive and negative surges, maximum instantaneous stresses were recorded well in excess of the critical shear stress for sediment inception, nearly independently of the bed roughness (Chanson 2010, Leng and Chanson 2015a). The surge generation was further associated with a rapid acceleration of the positive/negative surge's leading edge immediately after gate operation, until the surge propagation becomes more gradual. This is illustrated in Figure 6 showing the celerity of positive and negative surge front as a function of the distance from the gate. In practice, the successive rapid closure and opening of the gate provide the optimum conditions to scour silted channels made of fine cohesive and non cohesive materials, with the scour materials being rapidly advected downstream after the gate operation. A similar method is already implemented in sewers (Riochet 2008).

During recent tsunami disasters, a number of observations showed massive inundation caused by tsunami waters following river courses, as well as major damage caused during the backrush along the estuarine channels. While the former was well documented (Adityawan et al. 2012, Tanaka et al. 2014), the latter is less well known. During the 2010 Chilean tsunami, retreating tsunami currents approached 6–7 m/s at the Ventura Harbor channel (California) causing significant scour at the mouth of the harbour. During the 2011 Tohoku earthquake and tsunami, significant erosion and scour of the subsurface soil deposits was caused by repetition of inflow and backrush of the tsunami in the river systems.

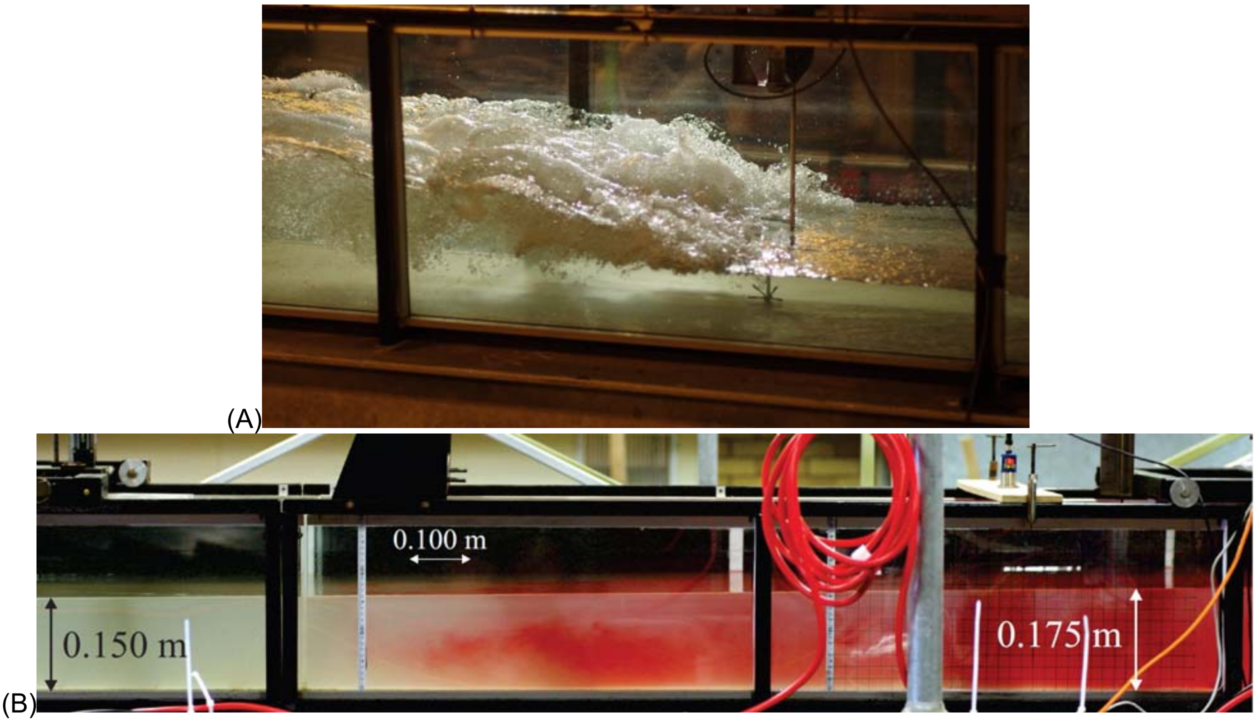

Figure 5. Positive and negative surge in conveyance canals propagating upstream (from left to right). (A) Positive surge generated by a rapid gate closure (Q = 0.099 m^3/s, S_o = 0.0077, W = 0.7 m); (B) Negative surge induced by a rapid opening of a downstream gate in an initial steady flow (Q = 0.020 m^3/s, S_o = 0, W = 0.5 m) - rapid red dye dispersion beneath the negative surge.

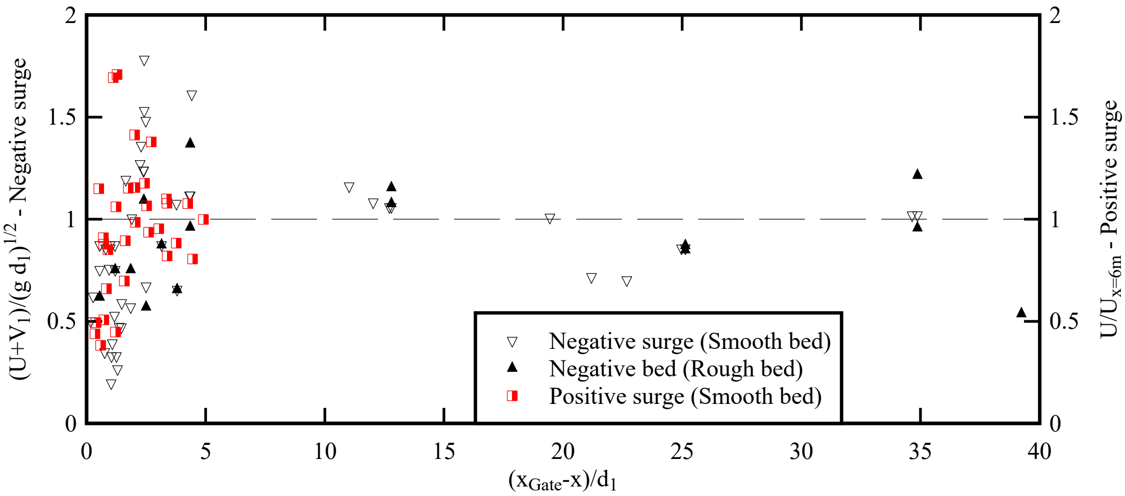

Figure 6. Instantaneous dimensionless celerity of positive and negative surge in conveyance canals during surge generation by a very-rapid gate closure as a function of the dimensionless distance from the gate. Negative surge data (black symbols): Reichstetter and Chanson (2013), Leng and Chanson (2015a). Positive surge data (red symbols): Reichstetter (2011).

3.2 Challenging surges

Positive and negative surges are most common in hydropower canal (Fig. 1B), water supply channel systems and navigation canals. The canal operation in an active regulation mode generates both positive and negative surges, including complicated interactions between successive surge events, surge reflections and transient forces on man-made structures. These phenomena have many practical consequences, including in terms of the freeboard of the canals, potential hydro-turbine operational restrictions, shipping conditions, while frequent pressure fluctuations cause high structural loads on regulation gates, navigation locks and gate seals. A major research finding has been that the visual appearance of the surge does not provide a reliable proxy of the turbulent Reynolds stresses generated by the surge propagation nor the potential for bed scour. This seminal, yet counterintuitive result implies that traditional one-dimensional modelling, and generally any depth-averaged model, cannot deliver reliable predictions of the hydrodynamic impact of surges. Fluid-structure and fluid-sediment interactions need to be resolved at the smallest scales through detailed three-dimensional modelling, physical and/or numerical CFD.

With breaking surges (Fig. 5A), a further complication is the turbulent two-phase flow roller motion. The breaking roller propagates upstream in a highly turbulent fashion. Although its mean bore celerity U is quasi-constant, the instantaneous celerity u fluctuates rapidly with both time and transverse location. The instantaneous roller toe forms a pseudo-continuous curve, i.e. the roller toe perimeter, where the abrupt change in water depth is a flow singularity, as well as a line source of entrained air and of vorticity (Leng and Chanson 2015b, Wang et al. 2017). Experimental measurements of the roller toe perimeter based upon high-speed video cameras showed a wide range of instantaneous toe perimeter shapes, with very rapid variations with time and space. The longitudinal motion of the roller suggested a pseudo-two-dimensional fluctuating behaviour, including some backshifts from time to time, with a ratio of standard deviation to temporal mean celerity u'/U ~ 1 (Leng and Chanson 2015b). Such large fluctuations are linked to the generation and advection of large coherent structures in the roller, associated with air entrapment in the breaker (Leng and Chanson 2019). The transverse profile of the roller toe perimeter presented some pseudo-periodicity with a characteristic transverse wavelength L_w such that $1 < L_w/d_1 < 10$ mostly (Chanson 2016, Wang et al. 2017).

4 UPSTREAM FISH PASSAGE AT ROAD CROSSINGS

4.1 Fish passage in culverts

Waterway crossings, including culverts, are common hydraulic structures along rivers and streams, in rural and urban water systems. A culvert is a covered channel allowing the passage of flood waters beneath an embankment, for example a roadway. The designs are very diverse, using various shapes and construction materials determined by stream width, peak flows, stream gradient, road direction and minimum cost (Herr and Bossy 1965, Chanson 2004). During operation, the fluid flow motion in a culvert is complicated because of the boundary conditions and flow turbulence. The road crossings create physical or hydrodynamic barriers that often prevent or reduce access to essential spawning, breeding and feeding habitats. The negative impacts on freshwater flora, fauna and fish species have been well documented in the literature (Warren and Pardew 1998). The manner in which culverts block fish movement encompass perched outlets, high velocity and insufficient water depth in the culvert barrel, debris accumulation at the inlet, and standing waves in the outlet or inlet, all of which being closely linked to the targeted fish species (Katopodis 1999, Olsen and Tullis 2013).

While a number of fish passage studies have been conducted in laboratories, the extrapolation of the results to full-scale hydraulic structures is far from trivial, because most studies do not fulfill the basic similarity requirements for a number of key relevant dimensionless parameters, including the intrinsic limitations of current fish swim tunnel tests and lack of standardisation (Katopodis and Gervais 2016, Wang and Chanson 2018a,b). A few studies recorded quantitative detailed characteristics of both fish motion and fluid flow (Nikora et al. 2003, Plew et al. 2007). Fewer investigations reported fish speed fluctuations and fluid velocity fluctuations, and fish response time and integral time scales (Wang et al. 2016, Cabonce et al. 2018). All the results showed that several key parameters, including the ratios of fish speed to water velocity fluctuations, fish response time to turbulence time scale and fish length to turbulent integral length scale are scale dependant when the same fish are used in laboratory and in the field (Wang and Chanson 2018a). In other words, a complete similarity between laboratory data and full-scale observations is un-achievable, and one must seek full-sale modelling. For example, Figure 7 presents an endurance test of small-bodied fish in a full-scale box culvert barrel cell channel (12 m long, 0.5 m wide).

4.2 Modelling upstream fish passage in box culverts

Recent field observations and full-sale laboratory studies documented fish swimming and behaviour in box culvert barrels (Blank 2008, Wang et al. 2016, Cabonce et al. 2019). In smooth box culverts, all the data showed the fish swimming preferentially next to the walls particularly in the bottom corners, in regions of low velocity, high turbulence intensity and intense secondary motion (Fig. 8). This seminal finding is fundamental and shows the "sweet spots" that the fish exploit. The barrel bottom corner regions are low velocity zones where secondary motion is strong and the fish interact with strong coherent vortices. The fish "dance" with the turbulent vortices to minimise their associated energy consumption. Upstream passage cannot be successful when the fish fight the turbulence! Fish swimming tests in a full-scale box culvert barrel channel hinted two preferential responses of fish to turbulence and turbulent structures. In the first mode, the fish would react passively to vortical structures, their slow response possibly enabling them to be advected by the flow turbulence: e.g., in recirculation zones and secondary currents. In the second mode, the fish would be pro-active and respond very rapidly to a change in turbulent flow conditions, using the changes in instantaneous flow conditions to migrate upstream (Wang et al. 2016, Cabonce et al. 2018).

Figure 7. Juvenile silver perch (*Bidyanus bidyanus*) (L_f = 49 mm, m_f = 1.4 g) swimming upstream in the bottom left corner of a 12 m long 0.5 m wide culvert barrel channel equipped with small triangular baffles on one side (Spacing L_b = 0.67 m, Height h_b = 0.067 m) against a steady flow (Q = 0.0556 m^3/s, V_{mean} = 0.684 m/s, d = 0.163 m, S_o = 0) - Flow direction from left to right, with fish resting upstream of a corner baffle about 9 m upstream of the outlet.

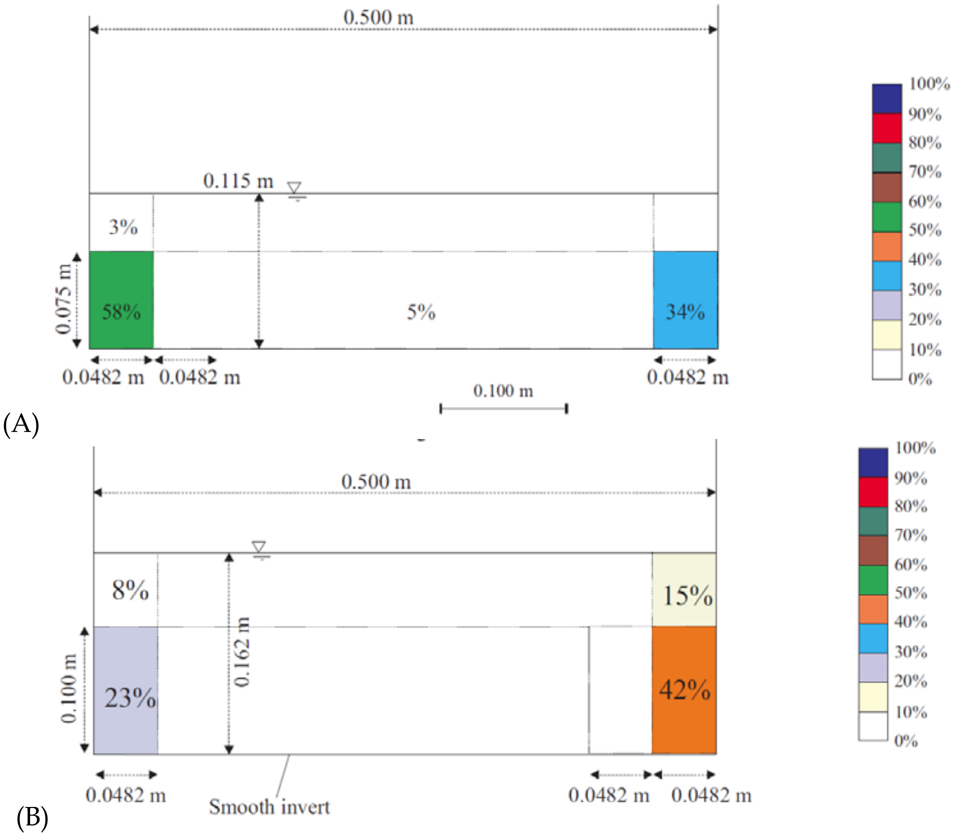

Figure 8. Percentage of time spent by small-bodied fish, Duboulay's rainbowfish *Melanotaenia duboulayi* (top) and juvenile silver perch *Bidyanus bidyanus* (bottom), within a smooth 12 m long 0.5 m wide culvert barrel channel cross-section, weighted with respect to time at less-than design flow conditions: (A) $Q = 0.026$ m^3/s, $V_{mean} = 0.54$ m/s; (B): $Q = 0.0556$ m^3/s, $V_{mean} = 0.69$ m/s. Data: Wang et al. (2016), Cabonce et al. (2019).

In the view of ecologically-friendly engineering design, which has motivated many studies, a comprehensive understanding of fish behaviour is a pre-requisite for advanced studies, including how fish sense fluid flow turbulence to select optimum upstream path in turbulent flows. The most interesting, and probably the most important, investigations concern the simultaneous characterisation of both fish and fluid kinematics (Nikora et al. 2003, Plew et al. 2007, Wang et al. 2016, Cabonce et al. 2018). Fish kinematics, based upon high-speed video movies, may deliver seminal insights into the fluid-fish interactions, including fish trajectories, fish speed and acceleration, tailbeat frequencies and fish swimming energetics in turbulent flows. Further investigations should consider the characteristic fish acceleration frequencies as well as the autocorrelation time scales of the fish acceleration, and a quantitative description of the fish energy consumption during their upstream migration in canonical turbulent flow motions.

5 CONCLUSION

While hydraulic structures have been used for millenia, the 21st century brings a number of new challenges for the hydraulic engineers, for which a combination of innovative engineering, research excellence and broad-based expertise constitutes a basic requirement. This keynote paper re-visits the self-aeration processes at hydraulic structures, the transient turbulence generated in conveyance structures during surge events, and the upstream fish passage in box culverts. While all these topics have been previously investigated with simplified models, a number of technical solutions are not satisfactory in terms of aquatic fauna and flora, fluid-structures interactions and operational restrictions.

Our knowledge of self-aerated air-water flows in hydraulic structures lacks insights into the physical interfacial phenomena at the millimetric and sub-millimetric scales, including the modulation of the turbulence, although the implications in terms of design have been well-known for decades, e.g. flow bulking, drag reduction, re-oxygenation. Similarly, the characteristics of transient turbulence during surge propagation in conveyance structures remains mostly ignored and the practical applications largely untapped, despite the millions of kilometres of water channels worldwide. The adverse impact of road crossings on aquatic life is an emerging concern. Biological science studies have been largely based upon pseudo-quantitative observations, although very recent engineering and bioengineering research has been undertaken, hinged on advanced physics-based theory supported by high-quality experimental data.

Although the second half of the 20th century marked a change in the perception of the structures by our society, these man-made waterworks shall continue to play a major role in human life and activities because water is an indispensable element. The technical challenges in hydraulic structure design are formidable for 21st century engineers. The future lies in strong links between engineering innovation, excellence in hydraulic research and quality education in universities. These interactions must be complemented by indispensable exchanges between professionals, researchers and educators in engineering and other fields, e.g. ecology, biology, geomorphology, water chemistry, geopolitics.

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Hubert Chanson has competing interest and conflict of interest with Craig E. Franklin.

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