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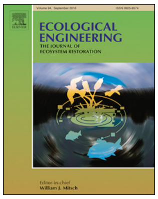

Short communication

Utilising the boundary layer to help restore the connectivity of fish habitats and populations. An engineering discussion

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ABSTRACT

While leading scholars emphasised the role of turbulence in waterways and the complex fish–turbulence interactions, what do we really know about turbulence? A recent paper developed a comparison between different boundary treatment to improve upstream passage of small fish in box culverts. The limitations of the work are discussed. It is argued that the practical engineering design implications cannot be ignored, while a solid understanding of turbulence typology is a basic requirement to any successful boundary treatment conducive of upstream fish passage.

1. Presentation

During the last decades, concerns about the ecological impact of culverts on stream connectivity have led to some evolution in design (Chorda et al., 1995; Warren Jr. and Pardew, 1998; Hotchkiss and Frei, 2007). The impact in terms of fish passage may adversely affect the upstream and downstream eco-systems (Briggs and Galarowicz, 2013). Common culvert fish passage barriers encompass perched outlet with excessive vertical drop at the culvert outlet, high velocities and turbulence in the barrel, debris accumulation at the culvert inlet, and standing waves in inlet and outlet (Behlke et al., 1991; Olsen and Tullis, 2013; Wang et al., 2018). Watson et al. (2018) presented a comparison between different boundary treatment to improve upstream passage of small fish in box culvert barrel. Implicitly their work was conducted for small water flow rates and not tested for large flood events corresponding to culvert design discharges. The writer has taught the hydraulic design of culverts to over 5000 Australian civil engineers from 1990 to 2019 at the University of Queensland, Australia, and he wrote a number of book chapters on hydraulic design of culverts (Chanson, 1999; Chanson, 2004; Chanson and Felder, 2017) and several review articles (Chanson, 2000, 2001, 2007). Based upon this experience and expertise, the paper argues that the testing procedure of the longitudinal beam design was biased and the practical engineering design implications cannot be ignored. It is shown that biological and hydrodynamic testings should be consistent with the engineering design approach of culverts. In particular, an understanding of turbulence typology is uppermost critical to a successful boundary treatment to restore connectivity of fish habitats and population at road crossings.

2. Longitudinal beam designs in a context

Channels with longitudinal beams have been studied for decades in chemical engineering, environmental and sanitary engineering, aeronautics, astronautics, biology and geology. Designs have been used for close to a century in water treatment plants (Randtke and Horsley, 2012). Longitudinal beams along channel walls has been successfully tested for the enhanced rate of heat transfer (Naik et al., 1999; Chang et al., 2008), mass transfer (Stamou, 2008), and biological filtration (Roo, 1965). Longitudinal ribs and beams are used in a number of stages of water treatment plants, e.g. maze flocculator, high-rate clarification tube settler, sedimentation basin with plate settlers, sludge clarifier (Degremont, 1979). Similar designs are incorporated into stormwater treatment systems and combined sewers (FNDAE, 1988). In alluvial channels, longitudinal troughs and ridges may develop along the mobile bed with preferential sediment transport mode (Nezu and Nakagawa, 1984; Shvidchenko and Pender, 2001). Small-size longitudinal beams can produce net drag reduction, with appropriate groove spacings (Bushnell and Mcginley, 1989; Choi et al., 1993). The scales of fast swimming sharks have fine longitudinal ridges, enabling faster swimming (Nitschke, 1983). A related application is the flow past seal fur, due to the streamwise fur pattern (Itoh et al., 2006).

3. Testing protocol: incompatibility with culvert design methods

The data of Watson et al. (2018) were presented for a constant bulk velocity irrespective of the boundary treatment, e.g. smooth (control), ledge, beam, baffles. Fig. 1 presents photographs of three boundary treatments: smooth (control), square beam, small corner baffles. The

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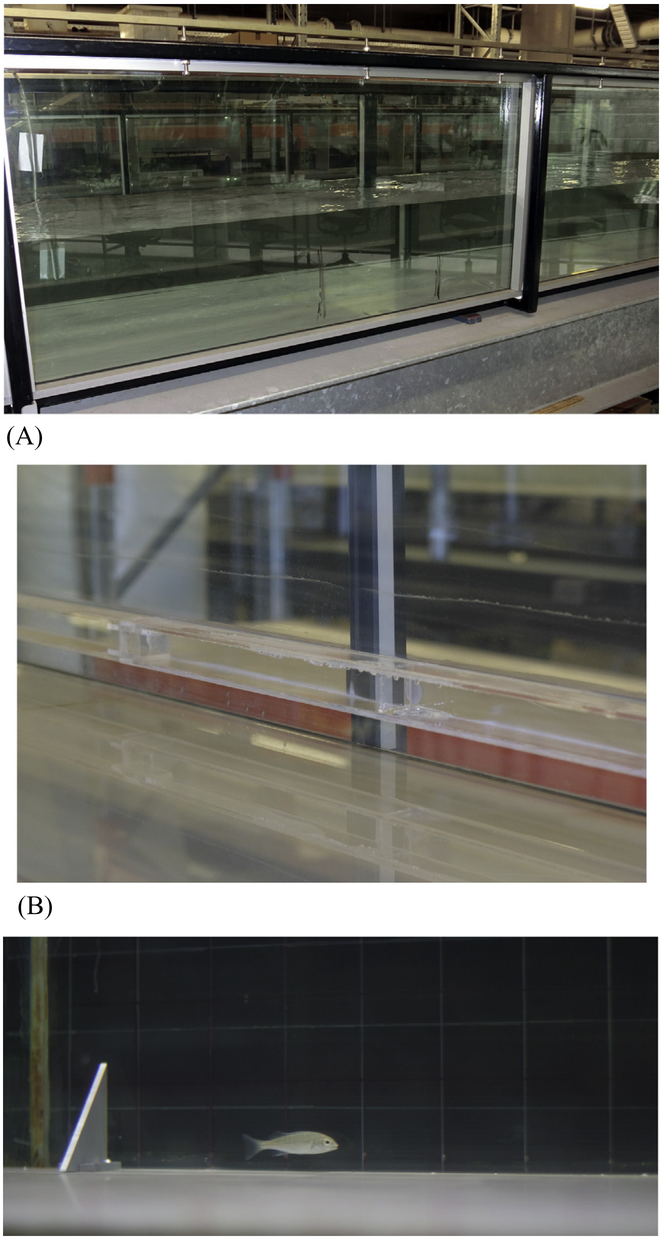
(A)

(B)

(C)

Fig. 1. Boundary treatment in a 0.5 m wide box culvert barrel channels - Flow direction from right to left.

experimental approach is questionable because (a) the bulk velocity is not constant along the channel in presence of a free-surface, in response to energy losses, gravity effect and tailwater conditions, and (b) the bulk velocity is not an engineering design parameter for culverts and road crossings.

In a horizontal rectangular channel, the water depth and velocity vary with longitudinal distance as functions of the boundary treatment and flow resistance (Henderson, 1966). The backwater profile would typically be a H2 profile (Chow, 1959), and the bulk velocity may vary by more than 20% depending upon the boundary conditions (e.g. Cabonce et al., 2017, 2019). Experimental observations in 12 m long 0.5 wide horizontal channel are presented in Fig. 2, and the facilities were similar to those used by Watson et al. (2018). For a unit discharge q = 0.111 m^2/s, the data of showed a bulk velocity increasing from 0.64 m/s to 0.71 m/s along the smooth (control) boundary flume, and from 0.54 m/s to 0.72 m/s with small triangular baffles (Fig. 2b). Furthermore, for a given bulk velocity at a fixed location, the water discharge changes in response to the boundary treatment and associated energy losses (Rouse, 1938; Chow, 1959; Sturm, 2001). Basic hydraulic engineering calculations demonstrate that, in the same 12 m long 0.5 m wide channel, the water flow rate increased by 10% to 25% from a smooth (control) condition to a triangular baffle treatment, to achieve the same bulk velocity. The rate in discharge increase is a function of the reference bulk velocity, sampling measurement location and tailwater conditions. Basically, the testing procedure of Watson et al. (2018) is strongly biased against, and would provide meaningless results for, high-flow resistance boundary treatment(s), e.g. triangular baffles, cross-bars, full-height sidewall baffles.

In practice, the hydraulic design parameters of culvert are the water discharge and afflux (Herr and Bossy, 1965; Concrete Pipe Association of Australasia, 2012; Chanson, 1999). The design of fish-friendly culvert design requires biological data compatible to engineering design procedures and useable by professional engineers (Katopodis and Gervais, 2016; Leng et al., 2019). A more appropriate methodology is the comparison of fish swimming performances between different boundary treatments tested with identical water discharge, as previously undertaken (Wang et al., 2016; Cabonce et al., 2017). For example, Cabonce et al. (2019) demonstrated conclusively some improved upstream traversability and endurance of juvenile silver perch (*Bidyanus bidyanus*) with small triangular corner baffles (Fig. 1c), compared to a smooth (control) channel geometry, for a relatively large discharge (q = 0.111 m^2/s). While a small fraction of small fish could be disoriented in the negative wake behind the baffle (Cabonce et al., 2018), the proportion of fish negotiating successfully the baffles were substantially larger, by nearly 50%, than in the smooth-wall control flume.

There are clear evidences that some boundary treatment can assist with upstream fish passage. At the same time, a number of boundary treatments have negative impact on the engineering design. in turn on the total cost, and possibly on the structural integrity of the structure with associated safety concerns for the human population. The design of fish-friendly road crossings and culverts cannot dissociate ecology, engineering and practical considerations.

4. Practical considerations of longitudinal beams - Design, manufacturing, installation, operation, blockage

The longitudinal beam design might provide some striking result in terms of fish passage and behaviour for very-small water discharges in idealised laboratory situation with PVC and glass surfaces. Its implementation to hydraulic structure designs must however be carefully considered within the engineering design of a culvert, because the beam does impact on the culvert operation and performances at small, medium and large water discharges, as well as on the upstream passage of larger fish.

The hydrodynamic motion in the longitudinal square beam channel leads to a complicated fluid dynamics. The strongest turbulence is generated in the corner regions, i.e. external and internal corners associated with the regions of sharpest curvature (Prandtl, 1952) (Fig. 3), and their effects are seen in most parts of the channel (Sanchez et al., 2018). Secondary currents develop as a result of the hydrodynamic singularities generated by the sharp corner edges, as sketched in Fig. 3. The sharp edges and corners of the square beam constitute well-known hydrodynamic discontinuity, conducive of strong secondary currents (Kennard, 1967; Gessner, 1973). The complex turbulent flow motion has further a marked effect on the flow resistance of the channel and in turn on the discharge capacity, as previously reported (Kennedy and Fulton, 1961).

A number of technical challenges encompass the manufacturing and installation of the beam (Fig. 1b), as well as operational considerations. The preferred manufacturing process of longitudinal beam channel would be in factory, to ensure that the beam position and alignment are

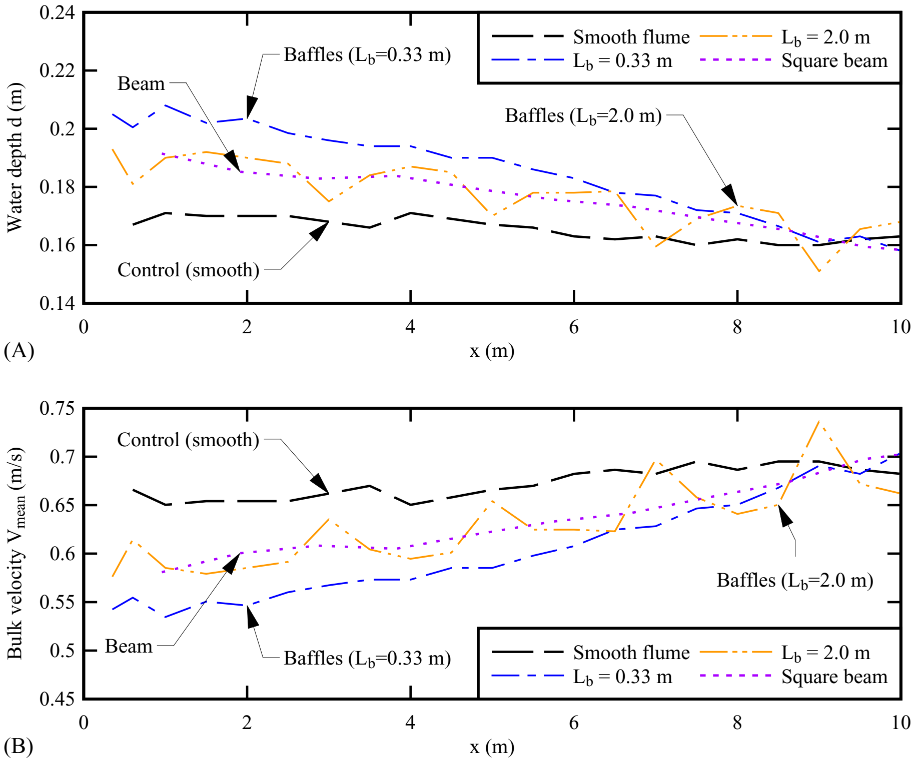

Fig. 2. Longitudinal profile of water depth d and bulk velocity V_{mean} in the 12 m long 0.5 m wide horizontal flume for Q = 0.0556 m^3/s. Comparison between control (smooth boundary) channel, channel with square beam, and channel with small triangular baffles (h_b = 0.133 m). Legend includes the longitudinal baffle spacing L_b. Data set: Cabonce et al. (2017, 2019), Sanchez et al. (2018). Note that the latter data set was adjusted to match the tailwater conditions.

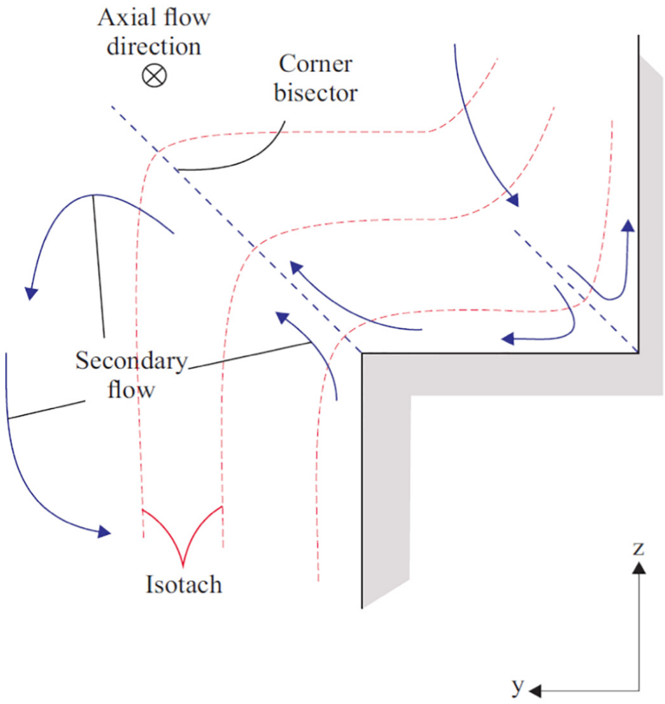

Fig. 3. Sketch of secondary current of Prandtl's second kind in a turbulent flow parallel to an outer corner, looking downstream.

within strict specifications. This is particular critical to ensure sharp edges, as any rounding would be most detrimental to the low-velocity zone size and culvert performance (Sanchez et al., 2018). An in-situ fitting would not meet the same standards, leading possibly to a substantially different flow field, with adverse impact on the culvert operation and function. In-situ installation, e.g. for retrofitting, would only be feasible in relatively large culvert cells: i.e. greater than 1.5 m to 1.8 m, and the installation tolerances are unlikely to be better than ± 10 mm.

The study considered 0.05 × 0.05 m^2 square beam, positioned 0.05 m above the floor. During operation, the cavity underneath the beam is at risk of siltation and sedimentation, as well as blockage. The accumulation of solid particles could lead to a partial or complete blockage of the low velocity regions, because the cavity flow is too slow and below current guidelines for self-cleaning (QUDM, 2013). Larger debris, including rocks, branches, trees, could also become jammed beneath the beam and ledge, obstructing the cavity and reducing further the culvert discharge capacity, thus impacting adversely on the upstream passage of both small-bodied and larger fish.

Simply, the usage of longitudinal beam in culverts must be considered carefully in a holistic fashion as part of the culvert design process. A number of practical considerations show major technical challenges during design, manufacturing, installation and operation. In many instances, alternative designs should be preferred and implemented, including asymmetrical large roughness and possibly small corner baffles.

5. Summary - And what about the boundary layer?

The title stated some "*utilisation of the boundary layer*". How? A boundary layer is a flow region where the hydrodynamic properties are affected by boundary friction (Schlichting, 1979; Bailly and Comte-Bellot, 2015). In a culvert barrel channel, detailed hydrodynamic measurements showed that the flow is fully-developed and the boundary layer occupies the whole flow area (Cabonce et al., 2017, 2019; Wang et al., 2018). While all configurations tested by the authors corresponded to some form of turbulent boundary layers, there were fundamental differences in the turbulence typology and key hydrodynamic processes, that cannot be ignored. With a smooth channel (control) (Fig. 1a), the dominant mechanism of energy dissipation is the boundary skin friction, with small secondary current of Prandtl's second kind in the bottom corners (Rodriguez and Garcia, 2008). In presence of longitudinal ledge and beam (Fig. 1b), strong secondary circulation of

Prandtl's second kind occurs, linked to the development of large streamwise vortices (Tamburrino and Gulliver, 2007; Sanchez et al., 2018), as well as surface longitudinal streaks (Levi, 1965). With small triangular baffles (Fig. 1c), the flow field is dominated by fluid streamline separation at the edge of each baffle (Cabonce et al., 2019), with a negative wake behind and boil of the first kind (Schlichting, 1979).

The interpretation of the turbulence typology is uppermost critical to a successful boundary treatment conducive to upstream passage of small-bodied weak-swimming fish. A precise knowledge of the entire three-dimensional velocity field is essential, because the rate of work and energy required by fish to thrust itself against the water discharge is proportional to the cube of the local fluid velocity, i.e. V_x^3 (Wang and Chanson, 2018). In a box culvert barrel, low velocity zones occur next to the bottom and walls, as well as at the bottom corners, and these highly-turbulent reduced velocity zones are the preferential swimming zones for small fish in box culverts, as shown by Gardner (2006), Wang et al. (2016), Cabonce et al. (2018, 2019). An in-depth understanding of the turbulent flow hydrodynamics constitutes a core requirement to comprehend the fish-fluid interactions, and a pre-requisite for physically-based mitigation measures of the ecological impact of culverts in terms of upstream fish passage. Researchers cannot be complacent about turbulence because it is ubiquitous in the nature: “*Turbulence is the most common, the most important and most complicated kind of flow motion*” (Bradshaw, 1971, p. xi) and “*many of its seemingly simple questions remain unanswered*” (Smits and Marusic, 2013, p.25).

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Declaration of Competing Interest

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

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