Hydrology & Water Resources Symposium

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30 November – 2 December

ISBN number for HWRS 2022 is 978-1-925627-64-0

Hydrodynamic instabilities and wave motion in fish-friendly box culverts equipped with full-height sidewall baffles

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ABSTRACT

Low-level river crossings and culverts deliver valuable transportation and hydraulic control services to the society, but have negative impacts in terms of upstream fish passage. Recently, full-height sidewall baffles have been imposed in north-eastern Australia to assist upstream passage of small-bodied fish in box culverts, although the impact on the culvert discharge capacity and flow motion was not assessed thoroughly. Herein, a near-full-scale physical modelling was performed to investigate the oscillation and instability of open-channel flow in a fish-friendly culvert equipped with full-height sidewall baffles. High-resolution measurements of the instantaneous flow velocity were conducted using an ADV Vectrino+ velocimeter. The physical results were marked by the existence of some low-frequency seiche phenomenon. The current study provides some further insights into the sustainable design of culverts to assist with upstream fish migration in man-made and natural fast channels. While the full-height sidewall baffles might assist fish passage at low flows, their impact on the culvert operation can be detrimental at medium to large flows.

INTRODUCTION

Fish migration is commonly seen in Australian waterways as a natural phenomenon. Many small-bodied fish species and juveniles of large fish, usually less than 100 mm total length, have very limited swimming performances, typically with characteristic swimming speeds less than 0.3 m/s (Chanson and Leng 2021). The construction of culverts can form ecological barriers, with adverse effects on the free movement of fish species. Some fish species, such as bony bream and mullet, are often observed to congregate at downstream of the entrance to culvert structures (Marsden et al. 2006). In Queensland only, there are more than 1,2000 such barrier structures that may prevent fish migrations (Dutton et al. 2021). Their negative effect on native fish species and biodiversity cannot be neglected.

The constructions of culverts have been enforced to maintain fish passage with dedicated design as required by some government regulations (DAF 2018). Wall roughening is proposed to be one of the common solutions to create some low-velocity zones to assist fish swimming against fast current in culverts. The installation full-height sidewall baffles is one of such designs "aimed" to create fish-friendly culverts (Marsden 2015, DAF 2018) and an example is shown in Figure 1. However, the culvert roughening may significantly reduce the capacity of flow conveyance, especially during flooding events with large flow rates (Leng and Chanson 2020, Li and Chanson 2020). Even though some field trials of the baffled culverts were conducted, the extents of the tests and investigated flow conditions were limited to very low flows (Marsden 2015, Dutton et al. 2021). There is still a need of proper hydraulic engineering analysis to cover the wide range of flow levels in the culverts equipped with full-height sidewall baffles. The current research focuses on the hydrodynamic instabilities in a near-full-scale facility, with the demonstration of large wavy undulations induced by sidewall baffles in culverts. This paper aims to stimulate some engineering considerations regarding fish-friendly culvert design, with the optimum spacing and ranging full-height sidewall baffles especially during large flooding events.

Figure 1. Box culvert equipped with full-height lateral baffles on wing sidewalls at Sandy Creek, beneath Flagstonian Drive, Flagstone QLD (14 August 2020) (Photograph H. Chanson).

EXPERIMENT SETUP AND FLOW CONDITIONS

Experiment Setup

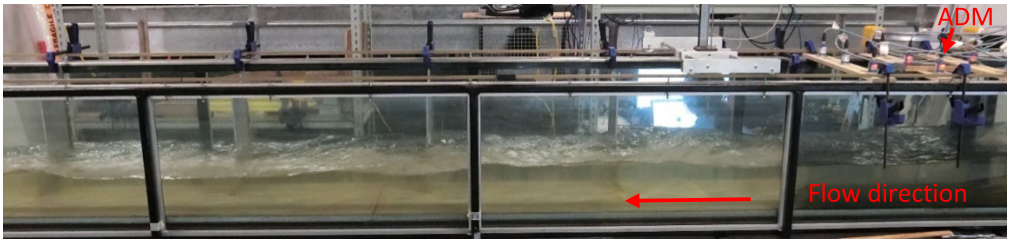
The physical modelling was performed within a 15 m long and 0.5 m wide (B = 0.50 m) open-channel flume (Fig. 2). The invert of the flume was made of smooth PVC and the sidewalls were made of transparent tempered glass. The channel bed was set at horizontal ($S_o = 0$). The water was conveyed to the test section through a 2.0 m long 1.25 m wide intake structure, supplied by a constant head tank. The intake basin was equipped with mesh, flow straighteners and a three-dimensional convergent leading to the 15 m long canal, to provide a smooth inflow into the flume. The flow had a free overfall at the end of the open channel.

A false floor was constructed between x = 0.6 m and 12.6 m, where x is the longitudinal location with x = 0 m starting from the upstream end of the test section. The beginning of the false PVC floor was contacted to the channel invert with a smooth quarter-rounding. The false floor bed was equipped with pre-installed threads to hold the baffle footings. A set of rectangular baffles, made of 6 mm thick PVC board, were installed along the right sidewall, extending up to 0.167 m from the wall. The baffle spacing interval was set as $L_b = 0.67$ m herein. The baffles were fixed to the false floor and then held with clamps at the top, as illustrated in Figure 2b, while clay was used to seal the gaps between the PVC baffles and glass sidewall. Table 1 contains a list of all the hydrodynamic parameters for the presented research.

Instrumentation

The water discharge Q was measured by a Venturi meter designed according to British standards (British Standard 1943), which was installed on the supply line of the constant head water reticulation system. The error of the flow rate was less than 2%. The centreline free-surface elevation was recorded with a pointer gauge, with an accuracy of ±0.5 mm in absence of visible free-surface undulations. Two high-speed video cameras, Casio™ EX-10 at 120 fps and Sony™ RX100 V at 100 fps, were deployed to record the instantaneous free-surface elevations through the sidewalls. A group of 9 ultrasonic acoustic displacement meters (ADM) Microsonic™ Mic+25 were installed above the flume and sampled at 200 Hz (Fig. 2). The sensors were calibrated beforehand against pointer gauge readings. The instantaneous velocities were recorded with an acoustic Doppler velocimeter (ADV) Nortek™ Vectrino+ equipped with a three-dimensional side-looking head. The ADV was set to sample at 200 Hz for 180 s at each sampling location. The vertical translation of the ADV unit was controlled by a fine adjustment screwdriver mechanism connected to a Mitutoyo® digital scale unit, with an accuracy of ±0.1 mm. The accuracy on the longitudinal and transverse positions was less than 2 mm.

(a)



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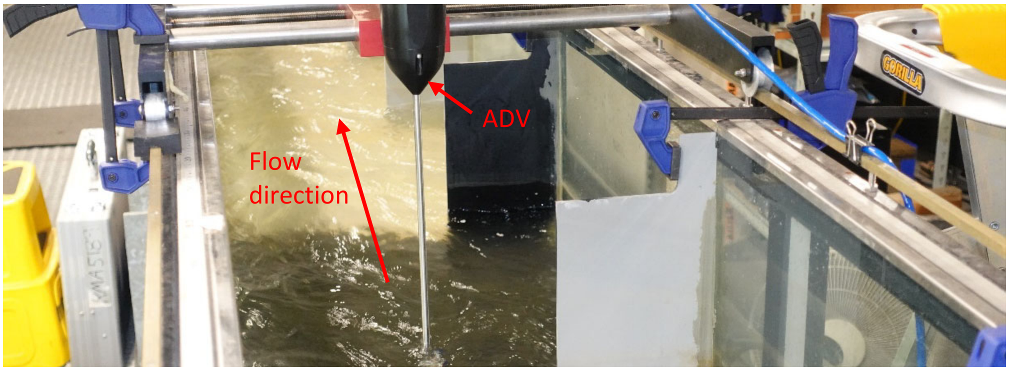

Figure 2. Physical modelling of open-channel flume with full-height sidewall baffles: (a) free-surface measurements; (b) velocity measurements. – Flow conditions: Q = 29 L/s, B = 0.5 m, L_b = 0.67 m, h_b = 0.167 m. – Note the ADM sensors, ADV and large wave motions.

Table 1. Summary of flow conditions.

Parameter	Value
Flow rate: Q	29 – 92.5 L/s
Channel slope: S_o	0
Channel length L:	15 m
Channel width: B	0.5 m
Baffle width: h_b	0.167 m
Baffle width: L_b	0.67 m
Reynolds number: Re	$(1.5 – 3.4) \times 10^5$

BASIC FLOW PATTERNS

Basic Flow Patterns

For all flow conditions, the flow in the baffled channel was very turbulent. The water surface presented a tumbling appearance, typical of natura torrents, although the laboratory flow was subcritical. Large-scale eddies were generated by the sidewall baffles and dye injection showed some complicated recirculation motion in the cavities between baffles. Large water surface elevation fluctuations were seen in the entire channel, i.e. in both the main flow and in the baffle cavities.

Detailed measurements were undertaken in the channel at 8.20 m < x < 8.87 m. The relative longitudinal coordinate was defined as $X_b = x - x_b$, where $x_b = 8.20$ m was the longitudinal location of the upstream baffle. The time-averaged flow velocity was derived from the ADV measurements at three different longitudinal cross-sections $X_b = 0.16$ m, 0.33 m and 0.50 m. The three-dimensional mean velocity distribution is presented in Figure 3. At each sampling point, the time-averaged flow direction is indicated by the arrow while the amplitude is represented by both the arrow colour and stem length in Figure 3. Altogether, the present data showed a complicated velocity field in the whole channel.

The installation of full-height sidewall baffles in the culvert cell significantly modified the flow patterns and velocity field. A high velocity zone (HVZ) was basically located in the main channel, i.e. 0.167 m < y < 0.50 m, with the velocity maxima larger than 0.8 m/s. A sharp transverse gradient in velocity occurred along the shear layer about the cavity opening (y = 0.167 m). The velocity field in the cavity (0 < y < 0.167 m) formed a low velocity zone (LVZ), with a three-dimensional coherent circulation structure, including some flow reversals towards the upstream end of the cavity (Li and Chanson 2020). As expected, the cavity between two consecutive baffles provided a LVZ with the maximum velocity less than 50% of that in the main stream, which could be utilised by upstream migrating fish individuals as a rest area.

Flow Resistance

The culvert roughening with sidewall baffles created some low velocity areas to assist with upstream fish migrations. The promotion of this design has not been popular among local governments and road departments, because of its negative effects on the hydraulic efficiency (Marsden 2015, Leng and Chanson 2020). In the current study, the water free-surface profile along the channel centreline was measured using a point gauge for each flow discharge. Then a theoretical profile was derived based on backwater calculation starting from the last downstream point in the baffled section toward upstream (Fig. 4). A series of attempts were performed with different trials of Darcy-Weisbach friction factor f to find the best-fit curve to the measurements.

During the current study, the best-fit backwater profile was achieved with the attempt of f = 0.39, compared to a smooth un-baffled channel flow resistance about f ≈ 0.015-0.02 (Cabonce et al. 2019). Therefore, the installation of full-height sidewall baffles increased the Darcy-Weisbach friction factor by 10 times, which was considerable. In terms of the Gauckler-Manning coefficient, this would represent an increase by a factor 5, but the readers are reminded that the use of the empirical Gaucklr-Manning coefficient in man-made channels is incorrect: "*The (Gauckler-Manning) equations express our continuing ignorance of turbulent processes*" (Liggett 1975, p. 45); "*Flow resistance calculations in open channels must be performed in term of the Darcy friction factor*" (Chanson 2004, p. 81-82).

In the practical design of fish-friendly culverts, the ideal proposal may be the comprise between construction cost, hydraulic efficiency and fish-passage capacity, which requires the modelling of different baffle intervals and widths to achieve consideration of all aspects.

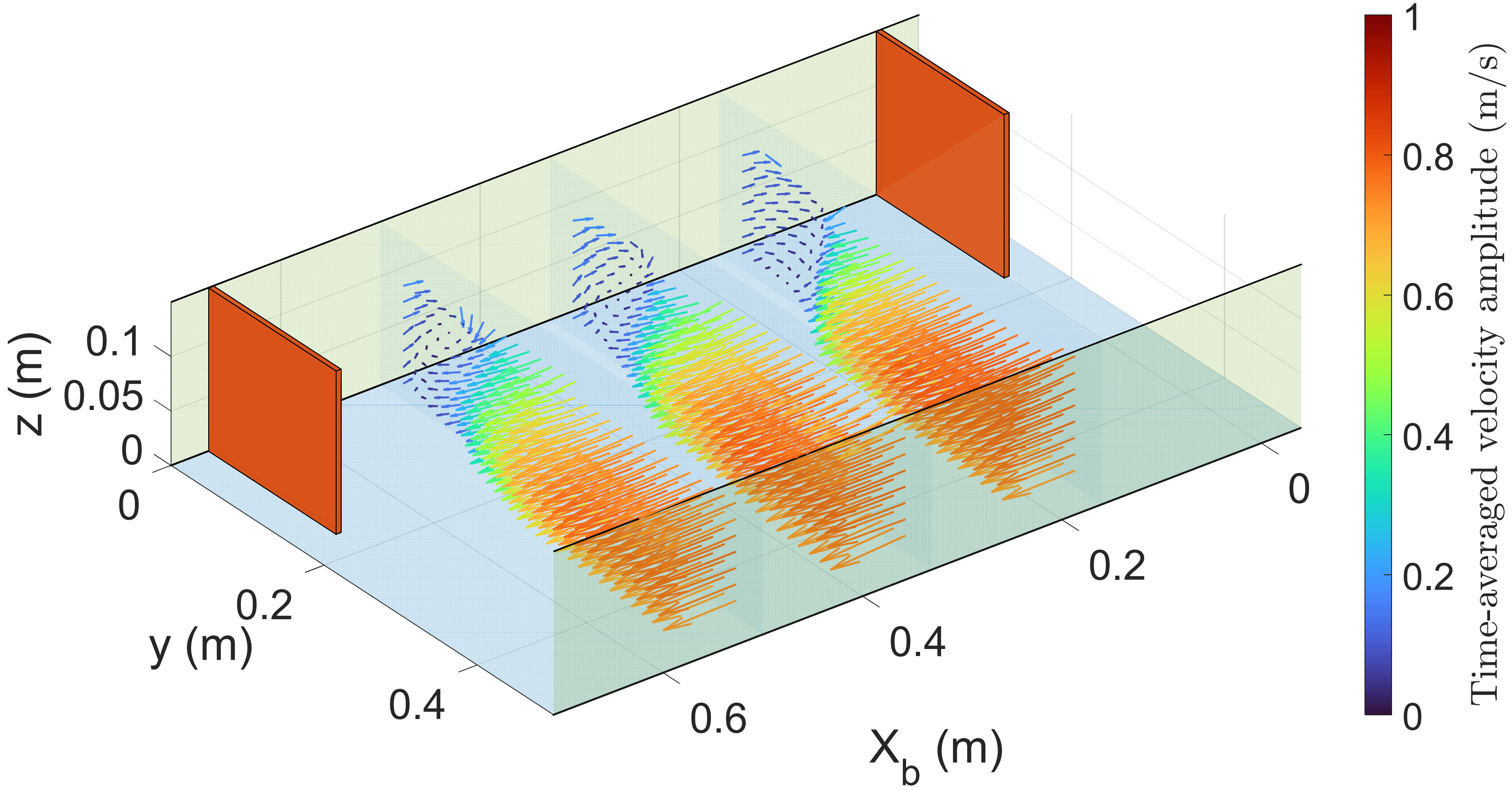

Figure 3. Time-averaged three-dimensional velocity field pattern in a cavity between two consecutive baffles. – The velocity vectors are indicated by the arrows, with their spatial coordinates located at arrow tails. The velocity amplitude is illustrated by the contour colour and linearly proportional to the length of arrow length. – Flow conditions: Q = 29 L/s, B = 0.5m, Lb = 0.67 m, hb = 0.167 m.

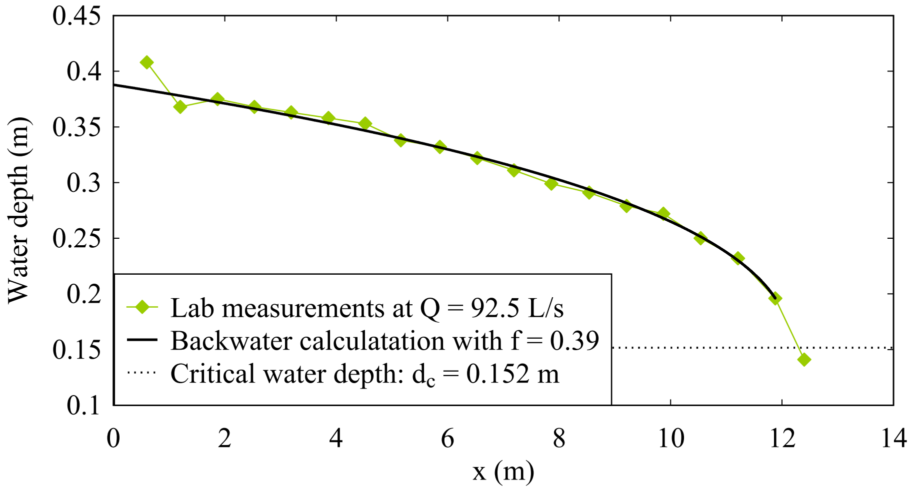

Figure 4. Flow profile in comparison with backwater calculation results. – Flow conditions: Q = 92.5 L/s, B = 0.5m, L_b = 0.67 m, h_b = 0.167 m.

Large Wavy Undulations

Visual, photographic and cinematographic observations indicated the presence of large water surface undulations along the baffled channel (Fig. 2a), briefly discussed by Leng and Chanson (2020). For comparison, the smooth channel flow presented free-surface roughness of ±0.5 mm. Herein, the analysis of instantaneous free-surface elevations was conducted based on both the side video recordings and ADM samplings. Two samples of the free-surface undulations are presented in Figures 5a and 5b. Both methods confirmed the existence of relatively large wavy undulations induced by the installation of sidewall baffles. The dominant undulation period was within the range of 0.3 – 0.5 s during the current observation. The measured period varied with different flow rates with a positive correlation between dominant wave period and water discharge. The statistical details of the instantaneous water elevation measurements, sampled at 200 Hz for 900 s, are included in Figure 5c. In Figure 5c, the minimum water depth d_{min}, the 1% percentile d_{1st}, median d_{50}, the 99% percentile d_{99} and the maximum water depth d_{max} are included for completeness. In this data set, the maximum wave height was about 20% of the mean water depth. More generally, the water undulation range reached in excess of 20% of the average water depth, which also induced some free-surface breaking with air-entrainment.

The wavy undulations were the characteristic of hydrodynamic instabilities within the baffled culverts. Therefore, some resultant periodic forces were applied onto the baffles. In prototype culverts (Fig. 1), the "DAF baffles" are typically installed anchored on culvert's walls and invert with nuts and bolts. The undulation-induced fluctuating loads could potentially be destructive, due to their relatively large amplitudes and periodic features. Combined with the potential impact of debris, the structural integrity of baffles and their associated fasteners may need to be revised in a more conservative manner based upon the experience during the 2011 Queensland floods (Murray and Kemp 2011, Australian Standard 2017, pp. 71-74). The robustness requirements of the fish-friendly culvert baffles may significantly increase the construction cost, which should also be considered.

(a)

(b)

(c)

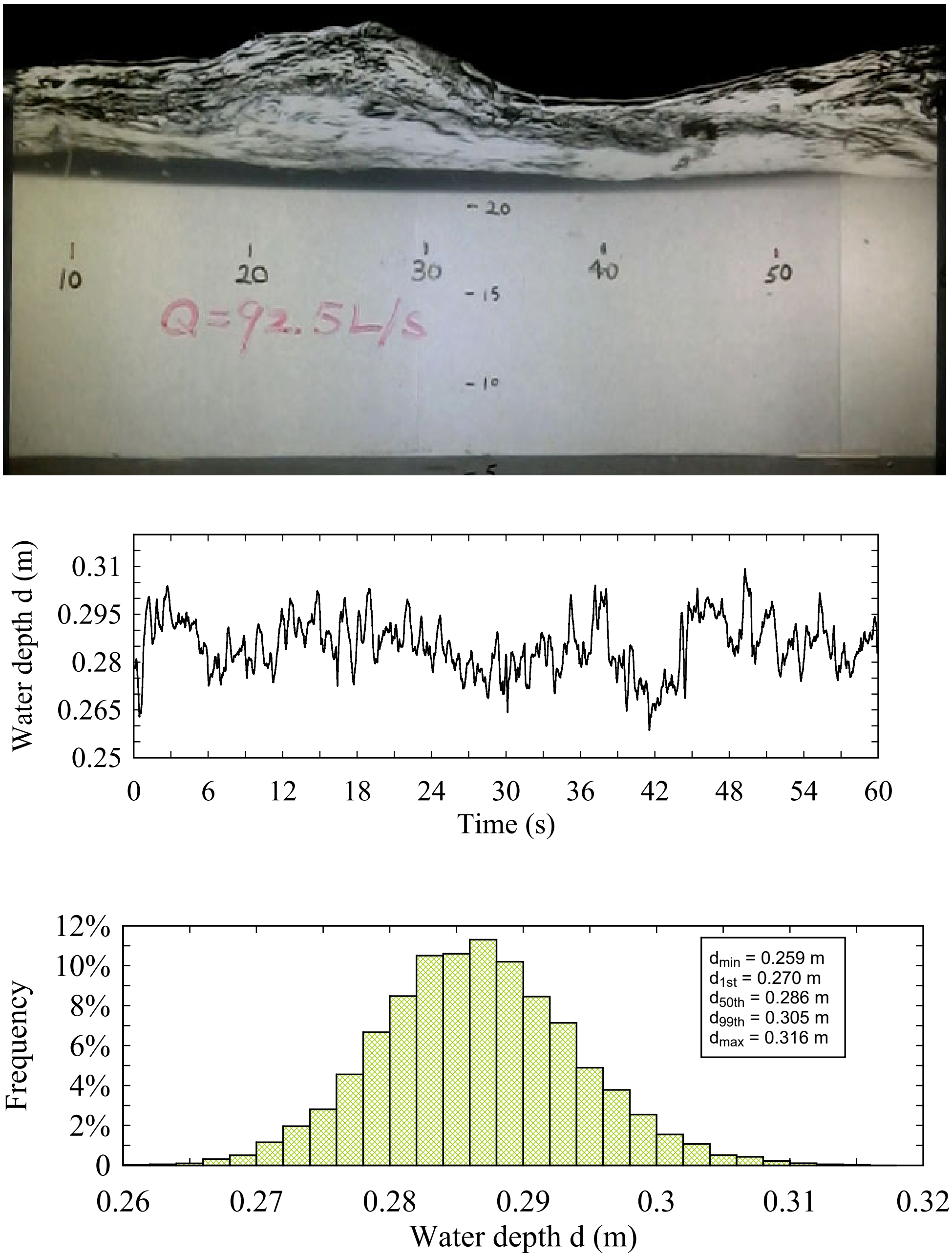

Figure 5. Free-surface elevation in the cavity between two consecutive baffles: (a) Snapshot of side video recording; (b) Sample of single ADM recording at 200 Hz in the cavity centre; (c) Statistics of single ADM recording at 200 Hz in the cavity centre. – Flow conditions: Q = 92.5 L/s, B = 0.5m, L_b = 0.67 m, h_b = 0.167 m.

Discussion

Fish-friendly culvert with full-height sidewall baffles are now commonly recommended in Queensland for new designs and retrofits. Based on the recent field trials and laboratory investigations, the cavities between consecutive baffles were proved to provide low velocity zones to assist with upstream fish migrations through fast currents in culverts. The flow resistance is increased due to roughening, which reduces the hydraulic efficiency and conveyance of the fish-friendly culverts. At higher water level due to flooding events, the hydrodynamic instabilities can be significantly increased with the occurrence of large-amplitude undulations. The robustness of the culvert structures may be negatively affected by the hydrodynamic instabilities due to large and periodic forces, which must be considered in the practical design. Further, at high discharges, the strong turbulent shear in the wake of each baffle might prevent the upstream fish progression, as small fish might not be capable to navigate past a baffle.

Since a culvert is a confined channel, a minimum freeboard must be provided between the water surface and the barrel obvert. General design guidelines for channels and culverts typically recommend a 20% clearance at design flow conditions (Chanson 2004, QUDM 2016 [sections 5.7 & 9.3], Chanson and Leng 2021). In presence of large wave heights, induced by the baffles, an extra clearance should be required to be added at 30% of the barrel water depth, because of the hydrodynamic instabilities, and the cost of the altered design would be accordingly increased.

In addition, the sidewall baffles are usually manufactured of steel, and installed next to the river banks as per DAF (2018). The baffles thus may cause potential threats to swift water rescuers and emergency personnel, e.g. during rescue missions by the Queensland Fire and Emergency Services (QFRS) (exchanges with A/Superintendent Graeme HALL, QFRS, December 2020), especially when a culvert is located close to a children playground. The above-mentioned problems need to be included for both further research and prototype constructions, inclusive of interactions with QFRS.

CONCLUSION

Culverts deliver valuable transportation and hydraulic control services to the society, despite negative impacts in terms of upstream fish passage. Recently, full-height sidewall baffles have been imposed in Queensland to assist upstream passage of small-body mass fish in box culverts, based upon very primitive testing and although the impact in terms of hydraulic was not assessed thoroughly. Herein, a near-full-scale physical modelling was performed to investigate the oscillation and instability of open-channel flow in a fish-friendly culvert equipped with full-height sidewall baffles.

While the full-height sidewall baffles might assist fish passage at low flows, their impact on the culvert operation can be detrimental at medium to large flows. The physical results demonstrated the existence of some low-frequency seiche phenomenon, associated with large wave heights. The extra clearance may be around 10% to preserve the dry culvert obvert conditions. The additional freeboard requirement would need to be considered into the budget planning of fish-friendly culvert proposals and constructions.

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BIOGRAPHY

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Hubert Chanson is Professor of Civil Engineering at the University of Queensland, where he has been since 1990, having previously enjoyed an industrial career for six years. His main field of expertise is environmental fluid mechanics and hydraulic engineering, both in terms of theoretical fundamentals, physical and numerical modelling. He leads a group of 5-10 researchers, largely targeting flows around hydraulic structures, two-phase (gas-liquid and solid-liquid) free-surface flows, turbulence in steady and unsteady open channel flows, using computation, lab-scale experiments, field work and analysis. He has published over 1,250 peer reviewed publications including two dozen of books. He serves on the editorial boards of International Journal of Multiphase Flow, Flow Measurement and Instrumentation, and Environmental Fluid Mechanics, the latter of which he is currently a senior Editor. His Youtube channel is: {https://www.youtube.com/channel/UCm-SedWAjKdQdGWNbCwppqw}.