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ARTICLE

How full-height sidewall baffles affect box culvert capacity: balancing fish passage and discharge requirements

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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 was ignored. Detailed physical modelling was conducted under controlled flow conditions in a near-full-scale culvert barrel channel, equipped with such full-height sidewall baffles. The results provide a quantitative assessment of the impact of full-height sidewall baffles on the discharge capacity of box culverts. Applications were developed for single- and multi-cell box culverts, and practical implications are discussed.

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Box culverts; sidewall baffles; upstream fish passage; discharge capacity; low-velocity zone; maintenance

1. Introduction

Low-level river crossings, including culverts (Figure 1(a)), are important for delivering a range of valuable socioeconomic services, including transportation and hydrological control. These structures are also known to have negative impacts on freshwater river system morphology and ecology, including the blockage of upstream fish passage, particularly weak-swimming fish species (Warren and Pardew 1998; Anderson et al. 2012). The manner in which culverts block fish movement is closely linked to the targeted fish species and may include perched outlet, high velocity in the culvert barrel, debris accumulation at the inlet and barrel, and standing waves in the structure (Behlke et al. 1991, Olsen and Tullis 2013).

Given the enormous environmental problems created by road crossings, various guidelines have been proposed for fish-friendly box culvert designs, albeit not always well-accepted (Leng et al. 2019). Recently, full-height sidewall baffles have been imposed in north-eastern Australia to assist upstream passage of small-bodied fish in box culverts across a wide range of discharges (DAF 2018), although the impact on the culvert discharge capacity was ignored. DAF (2018) specified the full-height sidewall baffle dimensions in the culvert barrel: $h_b = 0.150$ m and $L_b \leq 0.60$ m, to be installed on each bank, with h_b the baffle protuberance relative to the sidewall and L_b the longitudinal baffle spacing (Figure 1(b)). In practice, many designs use $L_b = 0.60$ m, i.e. $L_b/h_b = 4$.

Herein physical modelling was conducted under controlled flow conditions of a 12 m long 0.5 m wide culvert barrel channel, equipped with such full-height sidewall baffles. The measurements delivered a fine characterisation of the hydrodynamics of the baffled channel, acting as a box culvert barrel. The results provide a quantitative assessment of the impact of full-height sidewall baffles on the discharge capacity of box culverts. Applications are later developed for both multi- and single-cell box culverts.

2. Hydraulic facilities and instrumentation

The investigation was conducted in a 0.5 m wide horizontal rectangular channel, previously used by Sanchez, Leng, and Chanson (2019). Water was supplied by a constant head reticulation system and the flume ended with an overfall at the downstream end. The reference experiments were undertaken in the smooth flume equipped with a PVC bed. Several full-height sidewall baffles were subsequently tested: h_b = 0.042 m, 0.093 m and 0.167 m. The sidewall baffles were plain, geometrically scaled based upon DAF (2018), and installed on the right sidewall only (Figure 2). They were fixed to the floor and to the right sidewall.

The discharge was measured with a Venturi meter, designed according to British standards (British Standard 1943). A pointer gauge was utilised to measure the free surface elevation with an accuracy of ±0.5 mm. A Prandtl-Pitot tube (Ø3.18 mm) was used to measure the longitudinal velocity component. The Pitot tube was a Dwyer® 166 Series tube, meeting the AMCA and ASHRAE specifications and not requiring calibration.

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The experiments were performed in the horizontal channel, acting as a near-full-scale box culvert barrel, for a wide range of water discharges. Note that no inlet or outlet was introduced. As such, the influence of the inlet and outlet on the barrel flow conditions was not accounted for. Free-surface and flow resistance measurements were conducted for flow rates within 0.016 m^3/s < Q < 0.12 m^3/s, with all baffle sizes, i.e. h_b = 0 (no baffle), 0.042 m, 0.083 m and 0.167 m, and longitudinal baffle spacing L_b between 0.33 m and 1.67 m. All tests were conducted with full-height rectangular sidewall baffles installed along the right sidewall only. A constant baffle size and spacing was used for each configuration, as illustrated in Figure 1(b). Velocity measurements were undertaken for Q = 0.0556 m^3/s and one configuration: h_b = 0.083 m and L_b = 0.33 m.

3. Basic flow observations

Without and with baffles, the open channel flow was sub-critical and the longitudinal free-surface profiles presented a H2 backwater profile, with decreasing water depth with increasing longitudinal distance. In absence of baffle, the culvert barrel flow was smooth turbulent with a very smooth free-surface. The observations were similar to those of Wang, Uys, and Chanson (2018) and Cabonce, Wang, and Chanson (2018), 2019) in 12 m long 0.5 m wide smooth rectangular channels. The full-height

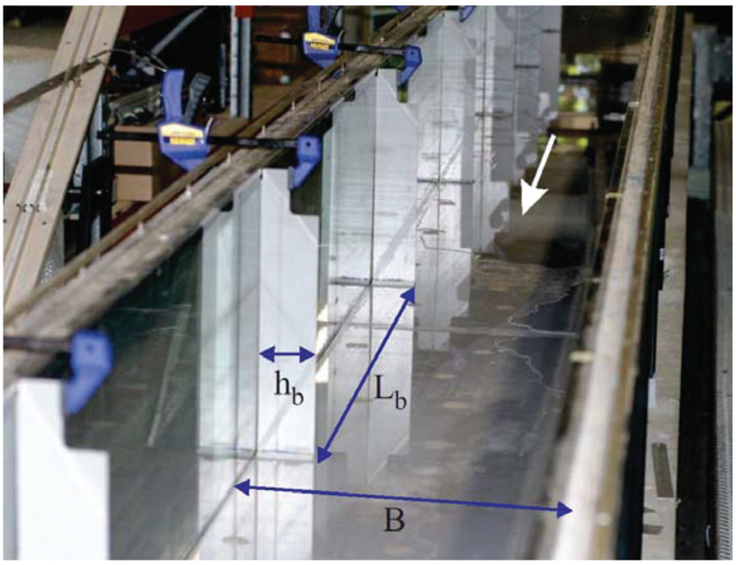

Figure 1. Photographs of a real-scale standard box culvert (no baffle installed) and a laboratory-scale culvert barrel model, equipped with sidewall baffles. (a) Box culvert inlet beneath the Ipswich Motorway at Oxley QLD (Australia) on 30 November 2019. (b) Box culvert barrel flume equipped with full-height sidewall baffles, looking upstream – configuration: h_b = 0.083 m, L_b = 1.33 m, B = 0.5 m.

sidewall baffles induced a very turbulent flow, for all investigated conditions, discharges and baffle sizes (Figure 2). The free-surface was very rough, with flow separation at each baffle and flow recirculation behind. Dye injection showed strong flow recirculation behind the baffles for all configurations and flow rates, with marked negative flows in the wake of the baffles. The recirculation patterns were functions of the relative longitudinal baffle spacing L_b /h_b and water depth. The recirculatory motion was

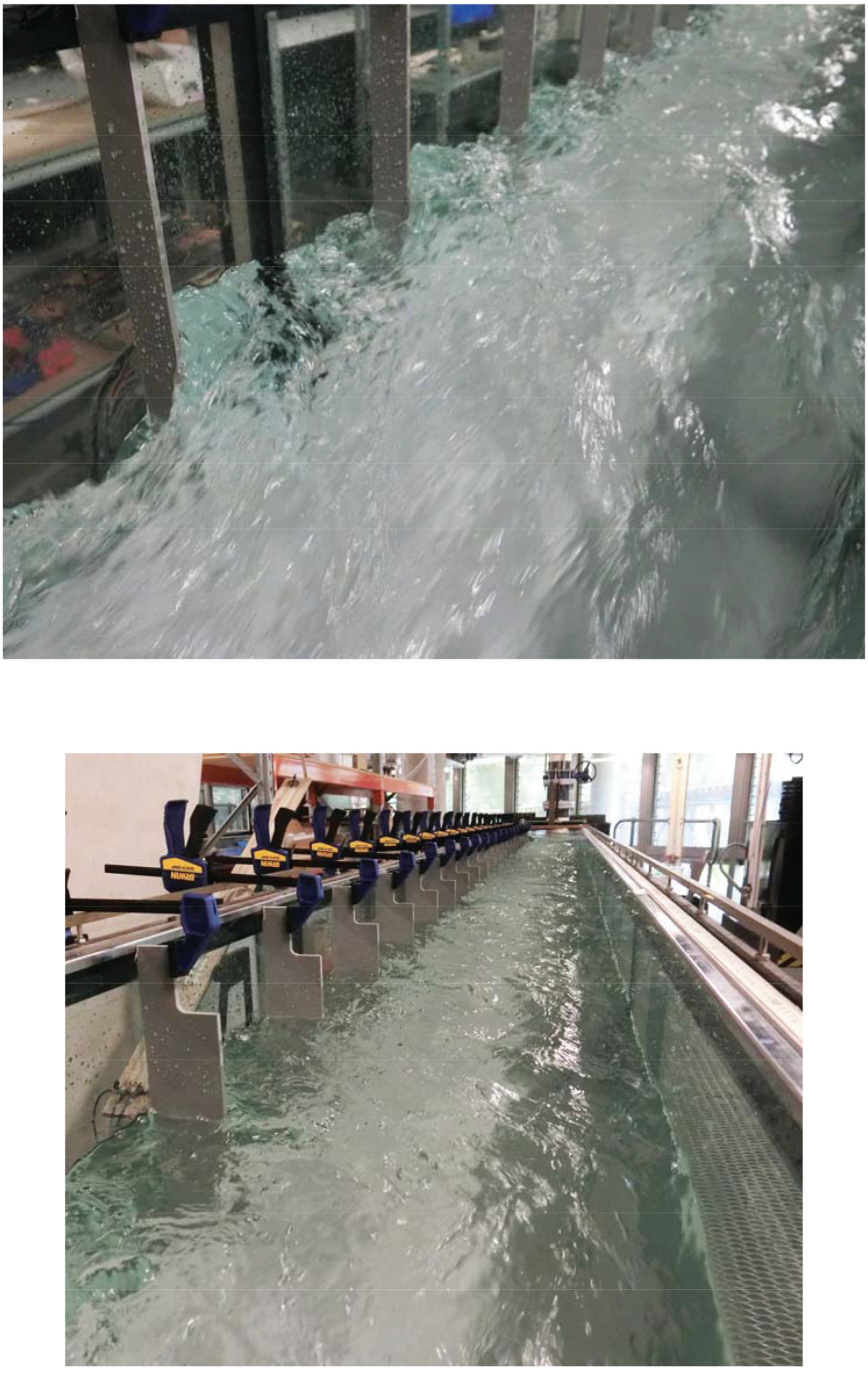

Figure 2. Culvert barrel operation with full-height sidewall baffles, looking upstream. (a) Small baffles: $Q = 0.110$ m^3/s, $h_b = 0.042$ m, $L_b = 0.33$ m (shutter speed: 1/125 s). (b) Medium baffles: $Q = 0.110$ m^3/s, $h_b = 0.083$ m, $L_b = 0.33$ m (shutter speed: 1/125 s).

mostly two-dimensional in shallow waters and it became three-dimensional in deeper water (Leng and Chanson 2019).

The rating curve of the culvert barrel channel was developed based upon the observed water depths at x = 8 m and the measured water discharges. Typical results are presented in Figure 3, where the data are compared to the critical flow conditions (thick red line). The results showed that all the experimental flow conditions corresponded to subcritical flows, with the observed water depths being greater than the critical flow depth. Further, all the data indicated that the sidewall baffles increased substantially the water depth in the barrel for a given flow rate, with the increase in depth being a function of the baffle configuration (Figure 3).

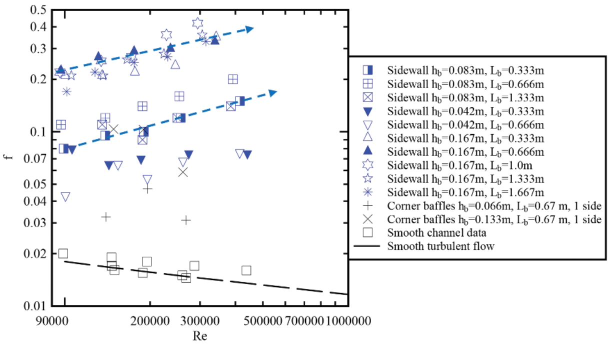

Figure 4. Flow resistance in a box culvert barrel equipped with full-height sidewall baffles along one sidewall: Darcy-Weisbach friction factor f as a function of the Reynolds number Re – comparison with the von Karman-Nikuradse formula for smooth turbulent flows (Chanson 2014) and bottom corner baffle data of Cabonce et al. (2019) (corner baffles on one side only) – dashed arrows show trendlines for increasing water discharge.

3.1. Flow resistance

The culvert barrel flow resistance was derived from energy considerations and the measured slope of the total head line, i.e. the friction slope. The dimensionless data are presented in Figure 4 in terms of the Darcy–Weisbach friction factor f as a function of the Reynolds number, in a presentation similar to the Moody diagram (Moody 1944; Chanson 2004). In Figure 4, the smooth channel data are compared to the von Karman-Nikuradse formula for smooth turbulent flows (Liggett 1994; Chanson 2014), while the full-height sidewall baffle data are compared to the data of Cabonce et al. (2019), with small bottom corner baffle installed on one side only.

The flow resistance in the culvert barrel equipped with full-height sidewall baffles was significantly larger than in the smooth channel, for the same flow conditions. The increase in friction factor corresponded up to 1 order of magnitude depending upon the baffle configuration and flow rate (Figure 4). The increased flow resistance was caused by the strong recirculation behind the baffles and induced secondary current motion. The associated turbulent dissipation contributed to a massive increase in total head losses, compared the smooth culvert barrel channel. With all the baffled configurations, the current data showed an increasing friction factor with increasing discharge, with trendlines drawn in Figure 4 in dashed blue arrows. In plain terms, the impact of the full-height sidewall baffles on the flow resistance increased with increasing water flow rate for a given configuration, being maximum at the maximum culvert design discharge.

The observation indicated some maximum in flow resistance for a relative longitudinal spacing of the baffles $L_b/h_b \sim 6$, with lesser flow resistance with shorter and longer baffle spacing L_b/h_b (Leng and Chanson 2019). The finding was not unlike experimental results on bottom cavity flows and transverse ribs (Adachi 1964; Knight and Macdonald 1979).

Altogether, the friction coefficient was a function of the channel width B/d, relative longitudinal baffle spacing L_b/h_b and relative baffle size h_b/B. For the current data set, the Darcy–Weisbach friction factor data were best correlated by:

$$f = \frac{\left(0.6633 \times e^{-0.1432\times(B/h_b)}\right)^{0.8} \times \left(0.35 \times 0.8931^{L_b/h_b} \times \left(\frac{L_b}{h_b}\right)^{0.5681}\right)^{0.2}}{\left(\frac{B}{d}\right)^{0.52}} \quad (1)$$

with a normalised correlation coefficient of 0.954. Equation (1) was developed for asymmetrical full-height sidewall baffles within $3 \le B/h_b \le 12$, $2 \le L_b/h_b \le 10$, and $9.6 \times 10^4 \le Re \le 4.4 \times 10^5$.

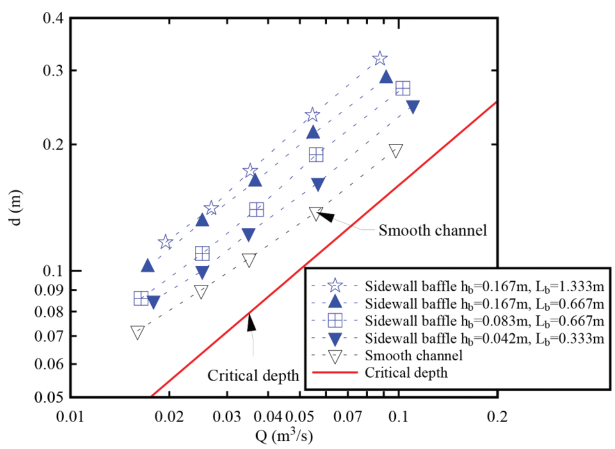

Figure 3. Relationship between the measured water depth at x = 8 m and the water discharge Q in the box culvert barrel channel equipped with full-height sidewall baffles.

3.2. Velocity contour maps

The velocity measurements showed a significant effect of the baffles in decelerating the flow, evidenced by decreasing velocity at all elevations with transverse distance closer to the baffle (right sidewall), in comparison to the smooth channel. Negative velocities were observed close to the right (baffled) sidewall for $0 < y/h_b < 1$, with y the transverse distance measured from the right sidewall (Figure 5). Figure 5 presents a typical velocity contour map between two baffles. All the data showed an asymmetrical distribution of the longitudinal velocity induced by the presence of baffles. The high-velocity flow regions were shifted towards the smooth (left) sidewall. Low-velocity zones were observed between the right (baffled) wall to almost twice the baffle size. In the wake of the baffle, the velocities were very small and the low-velocity zone showed a good longitudinal connectivity between the two adjacent baffles.

4. Discussion (1) On culvert discharge capacity including the effect of baffles

The impact of the full-height sidewall baffles was calculated in terms of the discharge capacity of standard box culverts. Two approaches were initially tested. In both cases, the reference geometry was the smooth culvert barrel. Method 1 was based upon a comparison of the water depth in the culvert barrel at x = 8 m, for subcritical flows (Figure 3). Such an approach (Method 1) used the experimental observations conducted with flow conditions corresponding to less-than-design flows.

Method 2 compared the discharge capacity of the entire culvert system for the same total head loss as the smooth culvert barrel operating with inlet control conditions. For inlet control operation, the culvert barrel operates with critical flow conditions (Chanson 2004; Concrete Pipe Association of Australasia 2012). With a 20% clearance between the free-surface and obvert, the maximum discharge capacity of a smooth box culvert barrel is ideally for a culvert barrel depth being critical:

$$Q_{des} = B_{cell} \times \sqrt{g \times (0.8 \times D_{cell})^3} \tag{2}$$

with B_{cell} and D_{cell} the internal barrel width and height, respectively. (It is acknowledged that the design conditions might differ from critical conditions and some culverts might operate under outlet control, including pressurised conditions, linked to the limitations of commercially available sizes.) The total head loss in the barrel may be predicted as:

$$\Delta H_{barrel} = f \times \frac{L}{D_H} \times \frac{V_{barrel}^2}{2 \times g} \tag{3}$$

where f is the Darcy friction factor of the culvert barrel (Equation (1) and Figure 4), combining both friction and form losses in the barrel, and V_{barrel} is the bulk velocity in the barrel. At the culvert outlet, the exit loss may be estimated from the Borda-Carnot formula (Chanson 2004):

$$\Delta H_{exit} = \frac{V_{barrel}^2}{2 \times g} - \frac{V_{tw}^2}{2 \times g} \tag{4}$$

where V_{tw} is the tailwater velocity in the downstream flood plain. For a given boundary treatment, the total head loss is basically:

$$\Delta H = \Delta H_{barrel} + \Delta H_{exit} \tag{5}$$

While both methods gave close results (Table 1), the second method (Method 2) should be deemed more relevant since it is based upon the maximum design flow conditions. It was later applied to Applications 2 and 3 (Tables 2 and 3).

4.1. Application 1. Culvert barrel (outer) cell

Let us consider a full-scale standard box culvert with 12 m long, 0.5 m wide and 0.4 m high barrel cells operating with inlet at ground level. Under inlet control, assuming a 20% clearance between the free-surface and obvert, the maximum discharge capacity of each smooth culvert barrel cell is 0.283 m^3/s. Assuming zero tailwater velocity, the total head loss of the smooth culvert structure would be 0.20 m at design flow, i.e. $(Q_{des})_{smooth}$ = 0.283 m^3/s per cell. With full-height sidewall baffles in a culvert cell, the head losses in the culvert barrel would be larger, and the exit form losses are lower because of the slower barrel velocities. In turn, the total head losses of the baffled culvert structure would be greater than those in the smooth box culvert cell, unless the design discharge capacity is reduced.

Detailed calculations were conducted for five sidewall baffle configurations (Table 1). The second and

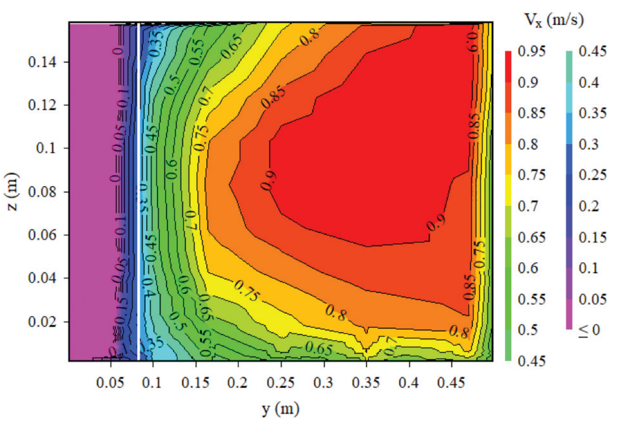

Figure 5. Streamwise velocity contour map at a dimensionless distance $(x–x_b)/L_b$ = 0.50 (i.e. half-way between two baffles) – flow conditions: Q = 0.054 m^3/s, h_b = 0.083 m, L_b = 0.33 m – thick vertical white line marks the outer edge of the sidewall baffles.

Table 1. Impact of full-height sidewall baffles (on one side only) on the discharge capacity of a full-scale standard box culvert barrel cell for a 12 m long, 0.5 m wide and 0.4 m high barrel (Application 1).

h_b (m) =	0.042	0.083	0.083	0.167	0.167	
L_b (m) =	0.333	0.333	0.666	0.333	0.666	
L_b/h_b =	8	4	8	4	2	
B/h_b =	11.9	6.0	6.0	3.0	3.0	
$(Q_{des})_{baffle}$ (m^3/s) =	0.196	0.154	0.138	0.126	0.111	Method 2
$(Q_{des})_{smooth}$ $/(Q_{des})_{baffle}$ =	1.27–1.37	1.57–1.67	1.65–1.73	1.9–2.2	2.0–2.11	Method 1
	1.45	1.84	2.05	2.35	2.55	Method 2

Calculations performed neglecting the impact of free-surface instabilities.

Table 2. Multicell box culvert application calculations (Application 2).

Property (units)	Smooth culvert	Baffled	Culvert (1)	Comments
Nb of cells =	3	3	4	
D (m) =	0.40	0.40	0.40	Internal barrel height.
B (m) =	0.90	0.90	0.90	Internal barrel width.
h_b (m) =	N/A	0.15	0.15	
L_b. (m) =	N/A	0.60	0.60	
d_{barrel} (m) =	0.32	0.32	0.32	With 20% clearance between water surface and obvert.
V_{barrel} (m/s) =	1.77	0.97 (2)	0.97 (2)	
f	0.011	0.183 (2)	0.183 (2)	
ΔH_{barrel} (m) =	0.028	0.140 (2)	0.140 (2)	Barrel head loss.
ΔH_{exit} (m) =	0.162	0.048 (2)	0.048 (2)	Outlet losses.
ΔH (m) =	0.188	0.188 (2)	0.188 (2)	Total head losses.
Q_{des} (m^3/s) =	1.53	1.07	1.58	For the whole structure assuming inlet control.

[a]On one side of outer cells only
[b]Baffled barrel cell only.

fourth configurations correspond to a dimensionless longitudinal spacing L_b/h_b = 4 comparable to the requirements in DAF (2018). The fifth configuration met the requirements of DAF (2018) with a smaller spacing and larger number of baffles which would increase both construction and maintenance costs. The complete results are reported in Table 1 (bottom rows) in the form of the ratio of the smooth culvert discharge capacity $(Q_{des})_{smooth}$ to the baffled culvert discharge capacity $(Q_{des})_{baffle}$. The results demonstrated a drastic reduction in design discharge capacity of the culvert barrel cell, by 1.4 to 2.6 depending upon sidewall baffle configuration (Table 1).

4.2. Application 2. Multicell box culvert

Let us consider a multicell culvert, equipped with three identical cells (B = 0.9 m, D = 0.4 m) and a 12 m long barrel. (a) Calculate the discharge capacity, and the corresponding total head loss, of the smooth culvert structure assuming inlet control operation and 20% clearance between the free-surface and obvert at the design flow rate. (b) If the outer cells are equipped with full-height sidewall baffles (h_b = 0.15 m, L_b = 0.6 m) on one side only, predict the increase in the number of cells required to achieve the same discharge capacity as the smooth culvert, without an increase in the total head loss.

4.2.1. Calculations

For a multicell culvert, the total head losses are the same for all cells, and the total discharge is the sum of the discharges in each cell.

(a) Under inlet control, assuming a 20% clearance between the free-surface and obvert in the 12 m long, 0.9 m wide and 0.4 m high barrel, the maximum discharge capacity of a single cell is 0.51 m^3/s (Eq. (2)). The capacity of the smooth culvert barrel with three identical cells is 1.53 m^3/s, i.e. 0.51 m^3/s per cell, and the total head loss of the smooth culvert structure would be 0.188 m (Table 2, 2nd column).

(b) With full-height sidewall baffles, the head losses in the culvert barrel are comparatively larger. The baffle configuration corresponds to L_b/h_b = 4 and B/h_b = 6. With a 20% clearance between the obvert and water surface in the outer cells, the relative width is B/d = 1.8. (Implicitly the effects of free-surface instabilities, that might require a greater clearance, are neglected.) Equation (1) predicts a Darcy–Weisbach friction factor in the baffled barrel cells: f = 0.183. The discharge capacity of an outer cell equipped with baffles on one side is 0.279 m^3/s (per baffled cell), with a total head loss of 0.188 m. This gives a total discharge capacity of the three cell culvert structure of 1.067 m^3/s (Table 2, 3rd column).

With a four-cell culvert, the total discharge capacity of the structure of 1.577 m^3/s (Table 2, 4th column). That is, a four-cell structure is required to achieve the same discharge capacity as the smooth three cell culvert, without an increase in the total head loss. The results are summarised in Table 2, assuming zero tailwater velocity.

4.3. Application 3. Single-cell box culvert

We consider a single-cell box culvert (B = 2 m, D = 0.9 m) with a 12 m long barrel. (a) Calculate the discharge capacity, and the corresponding total head loss, of the smooth culvert structure assuming inlet control operation and 20% clearance between the free-surface and obvert at the design flow rate. (b) If the barrel is equipped with full-height sidewall baffles (h_b = 0.15 m, L_b = 0.6 m) on both sides, predict the increase in barrel width required to achieve the same discharge capacity as the smooth culvert structure without additional total head loss.

4.3.1. Calculations

The current physical modelling results apply to a box culvert, equipped with baffles on one side only. For a single-cell culvert with full-height baffles along both sidewalls, the experimental results may be applied assuming that the left smooth wall of the experimental flume corresponded to the centreline of the single-cell barrel, based upon the method of images (Vallentine 1969; Chanson 2014) (Figure 6). Practically, the present findings may be applied using $B = B_{cell}/2$, where B_{cell} is the single-cell barrel internal width, as illustrated in Figure 6. (Herein, B_{cell} = 2.0 m for the smooth culvert.)

(a) Under inlet control, assuming a 20% clearance between the free-surface and obvert in the 12 m long, 0.9 m wide and 0.4 m high barrel, the discharge capacity of the smooth single-cell culvert barrel is 3.825 m^3/s (Eq. (2)), and the total head loss of the culvert structure would be 0.384 m (Table 3, 2nd column).

Table 3. Single-cell culvert application calculations (Application 3).

Property (units)	Smooth culvert	Baffled	Culvert ([1])	Comments
D (m) =	0.9	0.9	0.9	
B (m) =	2.0	2.0	4.49	Single-cell internal width.
h_b (m) =	N/A	0.15	0.15	
L_b. (m) =	N/A	0.60	0.60	
d_{barrel} (m) =	0.72	0.72	0.72	With 20% clearance between water surface and obvert
V_{barrel} (m/s) =	2.66	1.65	2.37	
f	0.009	0.245 ([2])	0.062 ([2])	
ΔH_{barrel} (m) =	0.024	0.245	0.098	
ΔH_{exit} (m) =	0.360	0.139	0.286	
ΔH (m) =	0.384	0.384	0.384	Total head losses.
Q_{des} (m^3/s) =	3.825	1.19	3.825	Assuming inlet control

[a]On both sides of single cell
[b]Using the method of images.

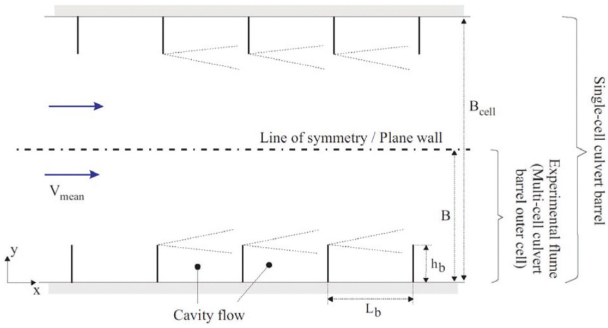

Figure 6. Plan view of a box culvert barrel equipped with full-height sidewall baffles – comparision between single-cell culvert and outer cell of multi-cell box culvert designs.

(b) With full-height sidewall baffles on both sides, the head losses in the culvert barrel are larger. With a 20% clearance between the obvert and water surface in the outer cells, the Darcy–Weisbach friction factor in the 2 m wide barrel would be: f = 0.245 (Eq. (1)). The discharge capacity of the baffled culvert is 1.19 m^3/s for a total head loss of 0.384 m (Table 3, 3rd column). This corresponds to a reduction of the discharge capacity by 69%.

A discharge capacity of 3.825 m^3/s for a total head loss of 0.384 m in a single-cell culvert equipped with baffles on both sides requires an internal width of 4.49 m (Table 3, 4th column). The results are summarised in Table 3, assuming zero tailwater velocity.

5. Discussion (2) Practical considerations

The above applications were undertaken based upon steady flow results, ignoring free-surface instabilities. As discussed by Leng and Chanson (2019), free-surface resonance and cavity sloshing may be observed under some flow conditions in the culvert barrel equipped with sidewall baffles. For the investigated baffle configurations and flow conditions, free-surface instabilities and standing waves were observed for a relatively narrow range of conditions. In first approximation, the oscillation period was linked to the longitudinal baffle spacing L_b, water depth d and channel width B: $T_L = 2\times L_b/(g \times d)^{1/2}$ and $T_B = 2 \times B/(g \times d)^{1/2}$ for the longitudinal and transverse instability modes, respectively, with g the gravity acceleration.

In presence of free-surface oscillations, a larger clearance between the free-surface and obvert might be required, e.g. 30% to 35%. For the configurations tested in Table 1, a 30% clearance between the water surface and obvert, for the full-height sidewall baffle culvert structure, would induce a further reduction in design discharge capacity of the barrel cell by up to one-third, compared to the results presented in Table 1, depending upon the sidewall baffle configuration. Simply, one cannot ignore the impact of free-surface instabilities on the culvert discharge capacity and

Figure 7. Massive debris blockage of a culvert inlet (white arrow) on Gillesbach stream, Aachen (Germany) on 1 May 2018.

more research work should be undertaken to quantify the free-surface instability characteristics.

During the culvert operation, sediment and debris trapping by the baffles may substantially reduce the discharge capacity of the structure, as well as impede upstream fish passage. Figure 7 illustrates an example of major culvert blockage by debris. The proper operation of the culvert over a wide range of discharges may imply a different maintenance programme, which must be linked to the targeted fish species (Chanson and LENG 2021). The maintenance plan has to be broad to ensure that both the culvert barrel's low-velocity-zone and its longitudinal connectivity, as well as the culvert discharge capacity, are not adversely affected by sedimentation and debris trapping. The clean-out might require manual handling and water jet, in tight and confined spaces.

While the effect of baffles is smaller for wide culvert barrel cells, the impact in terms of total costs is altogether very significant. Additional costs would encompass the installation costs of baffles, the increase in the number of barrel cells to achieve the same design discharge and afflux, and the costs of regular maintenance. In many cases when the discharge capacity cannot be compromised, alternative designs should be considered to assist upstream fish passage, e.g. small corner baffles, asymmetrical roughness, although the optimum type of boundary treatment shall be closely linked to the targeted fish species (Chanson 2019).

6. Conclusion

Physical modelling was performed in a 12 m long 0.5 m wide box culvert barrel channel, equipped with full-height sidewall baffles along one sidewall. Conducted for a broad range of discharges and baffle geometries, the results showed a massive impact of the full-height sidewall baffles on the flow conditions in the barrel. The data indicated in particular a substantial increase in flow turbulence and flow resistance. The results demonstrated conclusively a drastic reduction in discharge capacity of box culverts in presence of full-height sidewall baffles, with an increasing impact with increasing discharge for all baffle configurations. The physical modelling implied that the typical installation of full-height sidewall baffles proposed by DAF (2018) ($h_b = 0.15$ m, $L_b \le 0.6$ m) would reduce substantially the design discharge capacity of box culverts. This is illustrated with three detailed applications, although it is acknowledged that a larger clearance between the free-surface and obvert in presence of large free-surface instabilities.

In practice, the impact in terms of total costs is important, encompassing the installation costs of baffles, increase in the number of barrel cells to achieve the same design discharge and afflux, and operational maintenance. During culvert operation, sediment and debris trapping by the baffles would reduce further the discharge capacity of the structure and impede upstream fish passage. A proper operation of the culvert, over a wide range of discharges, requires a different approach to maintenance, associated to the targeted fish species. Such a maintenance would have to be thorough and might require manual and water jet clean out in confined spaces. In many cases when the discharge capacity cannot be compromised, alternative boundary treatment designs should be preferred to assist upstream fish passage.

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Notes on contributors

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