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Culvert Hydrodynamics to enhance Upstream Fish Passage: Fish Response to Turbulence

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Abstract

Waterway culverts are very common structures along water systems, ranging from rural roads to national highways and urban drainage networks. Current design guidelines are inadequate for fish passage, especially small-bodied Australian native fish species. Physical modelling was conducted in the laboratory under controlled flow conditions with the aim to maximise slow flow and recirculation regions suitable to upstream passage of small fish. An asymmetrical boundary roughness configuration was tested, consisting of a rough invert and rough sidewall, and the results were compared to a smooth boundary configuration. The hydrodynamic measurements showed the marked effect of boundary roughness on the distributions of time-averaged velocity and velocity fluctuations. Experiments were also conducted on two small fish species (Silver perch, Duboulay's Rainbowfish). This roughness configuration appeared to provide secondary current regions next to the rough sidewall and at the corner between the rough sidewall and channel bed.

Introduction

A culvert is a waterway designed to pass floodwaters beneath an embankment (Fig. 1 Left). In practice, the total cost of the structure must be minimum, and the optimum hydraulic design is the smallest barrel size allowing for inlet control operation [3]. The adverse role of culvert crossing on the riverine ecology has been recognised for the past decades, because the culverts limit the longitudinal connectivity of streams for fish movement [19]. Culvert fish passage is inhibited by a wide variety of parameters, including barrel velocities, culvert length, and insufficient water depth, which can influence fish swimming performance [2,12,15]. One primary ecological concern is the potential velocity barrier to upstream fish passage resulting from high velocities in the culvert barrel. Baffles may be installed along the barrel invert to provide locally smaller velocity, but the discharge capacity may be adversely affected [4,9,12].

The behavioural responses of fish to flow turbulence may play a role in their swimming ability and passage through a culvert. Recent discussions have indicated that three-dimensional flow studies are required to gain an understanding of fish-turbulence interactions [11,13]. This however requires large size facilities to ensure that the ratio of fish to turbulence length scales is close to unity. While the usage of large channels to test fish swimming performance is not new [5,8], the present study aims to combine carefully-controlled turbulent flow conditions and accurate instrumentations with fine spatial and temporal resolutions.. The results provide some characterisation of fish behaviour and kinematics to turbulence, in the context of small-bodied fish (40 mm < L < 200 mm) in the presence of secondary currents.

Materials and methods

Experiments were conducted in a 12 m long 0.5 m wide tilting flume in the The University of Queensland Bio-hydrodynamics laboratory. The flume was made of smooth PVC bed and glass walls, and its hydrodynamics with smooth boundaries were reported in [18]. The channel bed was horizontal. A rough bed and sidewall configuration was used, with the installation of very-rough matting on the invert and left sidewall, resulting in a 0.4785 m internal width (Fig. 1 Right). Herein 'left sidewall' means the left wall when looking downstream. The rubber mats consisted of square patterns: 0.0482 m by 0.0482 m for the bed, and 0.0375 m by 0.0375 m for the left sidewall. The water surface elevation z was measured from the top of the mats. The perimeter-averaged boundary shear stress was deduced from measured free-surface profiles in the fully-developed flow region. The equivalent Darcy friction factor was f = 0.07 to 0.12 for the rough boundary configuration, compared to f = 0.015 to 0.017 for the smooth PVC bed configuration of the same flume.

Figure 1. Physical modelling of culvert hydrodynamics. Left: prototype operation in Brisbane on 20 May 2009; Right: laboratory channel with rough bed and sidewall configuration

The discharge was measured by an orifice flow meter calibrated on site. Free-surface measurements were performed using a pointer gauge. Detailed velocity measurements were conducted using an acoustic Doppler velocimeter (ADV) Nortek™ Vectrino+ equipped with a three-dimensional side-looking head. The velocity range was ±1.0 ms^{-1} and the ADV signal was sampled at 200 Hz for 180 s at each point. The translation of the ADV probe in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit. The error on the vertical position of the probes was $\Delta z < 0.025$ mm. The accuracy on the longitudinal position was estimated as $\Delta x < \pm 2$ mm. The accuracy on the

transverse position of the probe was less than 1 mm. All ADV signals were post-processed as discussed in [18].

Fish swimming measurements were conducted using juvenile Silver perch (*Bidyanus bidyanus*) and adult Duboulay's Rainbowfish (*Melanotaenia duboulayi*) in the rough bed and rough sidewall channel configuration (Fig. 2). Fish were fasted for 24 h before being tested at 24.5 ±0.5 C. Fish were placed for 15 min at the downstream end of the channel with a bulk velocity no more than 0.2 ms^{-1}. This short conditioning phase allowed the fish to adjust to the flow and channel shape. After 15 min the fish were released and would typically travel upstream and recording would begin when individuals reached the designated test section (4.5 m < x < 6.5 m). Fish kinematics were recorded for 20 min. If fish showed signs of fatigue, the test would be stopped and fish removed from flume. After each test, the fish were weighted, measured and photographed. The number of test fish and length and mass data are summarised in Table 1. In this study, fish were selected randomly for each experiment, and each fish was tested once only.

Specie	Number	Mass median (g)	Mass std dev (g)	Length median (mm)	Length std dev (mm)
Silver perch	23	39.7	33.7	145	31.5
Duboulay's Rainbowfish	23	3.20	1.07	70.5	8.0

Table 1. Fish data. The table shows the number of test fish, the median and standard deviation of fish mass and total length.

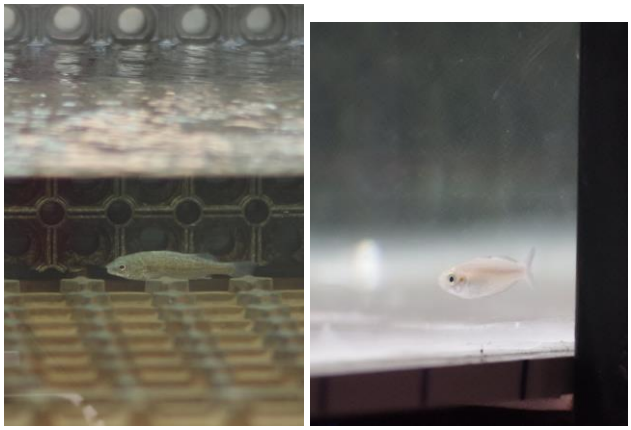

Figure 2. Fish swimming in the 12 m long flume, with flow direction from left to right. Left: juvenile Silver perch close to the rough sidewall; Right: Duboulay's Rainbowfish along the smooth sidewall

The positions of fish were recorded manually using a 3-D grid scale based upon the boundary roughness square pattern. These recordings showed that the fish spent most time in a reasonably thin vertical layer close to the rough sidewall and therefore the 2-D (vertical plan) projection of the fish trajectories may serve as an approximation of the 3-D trajectories. High-speed movies were recorded with a digital camera Casio™ Exilim EX-10, with movie mode set at 240 fps (512×384 pixels). Fish positions and movements were digitised off high-speed video images within 0.5 mm. Fish were tracked by their eye, since such a point on the body had the least lateral motion [14,17]. Semi-automatic tracking was performed using the softwares Tracker v. 4.91 and TEMA 2D Motion v. 3.9. Comparative tests showed close agreement between both softwares. Herein the trajectory data were smoothed using a Gaussian filter (7 points, unit standard deviation) [16]. Eulerian fish speed and acceleration were derived respectively from 1st and 2nd differentiation calculated using central differences at each time step. This filtering method was found to be robust for fish trajectories including both stationary and non-stationary time sub-series.

The experiments were conducted for one flow rate: Q = 0.0261 m^3s^{-1}. The channel flow was subcritical with decreasing water depth with increasing downstream distance. The inflow turbulence intensity was Tu ≈ 16%, with Tu = v_x'/V_x, v_x' being the standard deviation of the longitudinal velocity component and V_x the time-averaged longitudinal velocity component. At the upstream end of the channel, the flow field was quasi-uniform. Velocity data showed the development of a sidewall boundary layer at the upstream end of the channel, interacting with the bottom boundary layer. This led to some complicated secondary flow pattern further downstream, with some slow flow region next to the corner between the rough bed and sidewall. For x > 4 m, the flow became fully-developed, and most observations were conducted for 4.5 m < x < 6.5 m.

All experimentation was conducted with the approval of The University of Queensland Animal Ethics Committee (Certificate no. SBS/312/15/ARC).

Results

Hydrodynamics

Detailed velocity measurements were conducted in both the developing and fully-developed flow regions. Typical results in the fully-developed flow region are shown in Figure 3. The velocities in the channel were not uniformly distributed because of differences in boundary friction along the wetted perimeter and of the presence of the free-surface. The velocity field was not symmetrical about the channel centreline as illustrated in Figure 3, where y is the transverse distance from the right smooth sidewall, and y > 0 towards the left. The time-averaged longitudinal velocity data showed a complicated velocity pattern in the left bottom corner with the rough bed and rough left sidewall. A phenomenon of velocity dip is seen in Figure 3 (Top), in which the maximum velocity at each transverse location was observed at a vertical elevation beneath the free-surface. The dip in velocity profile was believed to be caused by the presence of secondary currents [1,10]. Low momentum fluid was transported from near the rough side wall to the centre and high momentum fluid was moved from the free surface toward the rough bed and sidewall. The maximum velocity and its location were found to be functions of the transverse locations. The cross sectional maximum velocity was observed below the free-surface towards the smooth right sidewall. Maximum velocity fluctuations were recorded close to the rough bed and rough sidewall. Along most vertical lines away from side walls, the longitudinal velocity fluctuations presented a local minimum below the free surface, at about the same elevation where the longitudinal velocity was maximum (data not shown). The cross sectional minimum values of longitudinal velocity fluctuations were about the centre line, while the cross-sectional maximum value was observed close to the bottom left rough wall. Contours of distributions of vertical velocity fluctuations, are presented in Figure 3 (Bottom). The vertical velocity fluctuation v_z' was reduced next to the free surface while v_x' was enhanced due to the water surface, as observed by [1].

Visual observations, supported by dye injection, showed some recirculation motion next to the left rough sidewall and at the corner between rough bed and sidewall. No similar vortex pattern was seen in the right side of the channel. Such secondary current motion may assist with the upstream passage of small fish.

Fish behaviour and kinematics

The recordings and observations of fish positions showed that for both fish species, the fish swam against the current (i.e. upstream) and they mostly swam in the corners of the flume. Observations for juvenile Silver perch are reported in Figure 4, indicating that the fish swam in the corners for more than 90% of the time. The smaller fish tended to prefer the corner where the

rough bed and rough sidewall induced a strong secondary current cell. Visual observations, and fish trajectory and speed data, for both species showed that the time-series could be sub-divided into (a) quasi-stationary motion where fish speed fluctuations were small, (b) short upstream motion facilitated by a few strong tail-beats, and (c) burst swimming when the fish would cross rapidly the entire observation window. The most common observation of fish swimming was the first one.

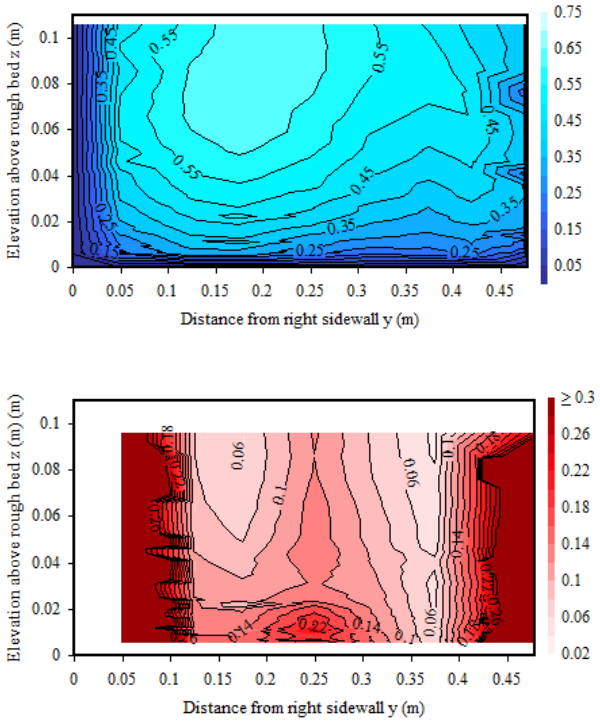

Figure 3. Contour curves of constant longitudinal velocity V_x (Top) and velocity vertical fluctuations v_z' (Bottom) with rough bed and rough sidewall - Q = 0.0261 m^3s^{-1}, x = 5 m, y = 0 at right smooth sidewall, velocity scale in ms^{-1}

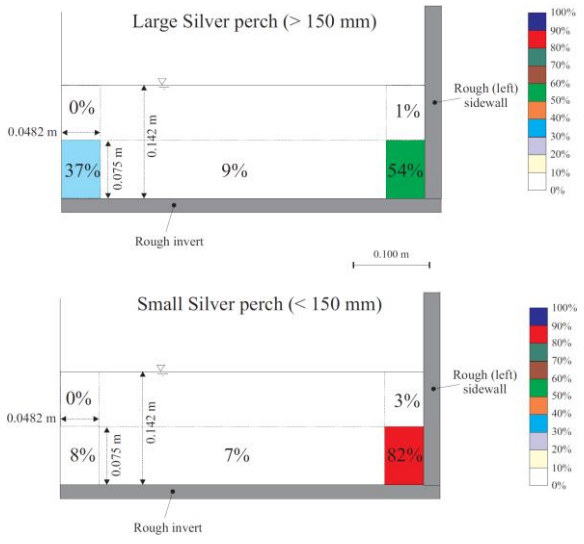

Figure 4. Visual observations of juvenile Silver perch position with respect to the rough bed and rough sidewall channel cross-section - Q = 0.0261 m^3s^{-1}, x = 4-6.5 m, y = 0 at right smooth sidewall (on left)

The fish trajectories, as well as the time-variations of fish speed and acceleration along these trajectories were analysed. Herein x is positive downstream and the (Eulerian) fish speed U_x and acceleration a_x are positive downstream. Overall the observations showed that the fish speed data were within ± 0.2 ms^{-1}, while the longitudinal fish acceleration was within ± 2 ms^{-2} (i.e. ± 0.2×g).

A typical example of longitudinal fish speed data set is shown in Figure 5, for an individual swimming in the bottom left corner (Right corner in Fig. 4). The data include the probability distribution functions of fish speed and power spectrum density function of fish speed.

The swimming velocity variability may be compared with the distribution of longitudinal fluid velocity component. In Figure 5 (Left), the probability distribution function of fish speed (red bars) is compared to the probability distribution function of the fluid velocity (blue bars). For both fish species, the ratio of fish speed to fluid velocity standard deviations was typically within $0.1 < u_x'/v_x' < 1$ with a median value about 0.25, independently of the fish species, length and mass, and v_x' the velocity fluctuations at the observation location. The results are reported in Figure 6 (filled coloured symbols). The fish speed fluctuations were systematically smaller than the fluid velocity fluctuations. Swimming in the corner of the flume may allow fish to minimise energetic costs associated with changes in acceleration [11]. Similarly the ratio of fish speed to fluid velocity auto-correlation time scales was within $0.3 < t_{xx}/T_{xx} < 3$ with a median value about 1.5 (Fig. 6). Since the fish speed auto-correlation time scale characterised a typical reaction time of the fish, the finding might suggest that the fish tended to react predominantly to the larger vortical structures, and did not modulate their speed in response to small and short-lived vortical structures.

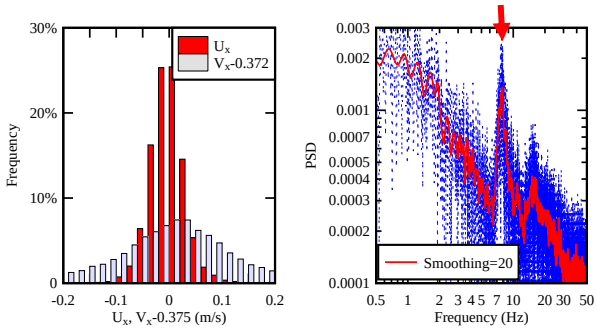

Figure 5. Fish speed and power spectrum density of fish speed of Duboulay's Rainbowfish No. 22 swimming along the rough sidewall

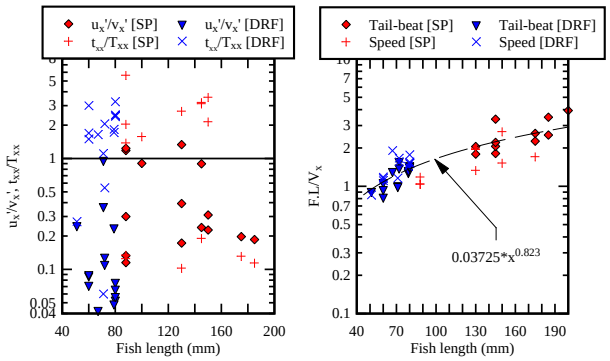

Figure 6 (Left). Ratio of fish speed to fluid velocity standard deviation and ratio of fish speed to fluid velocity auto-correlation time scales as functions of fish length: Silver perch [SP] and Duboulay's Rainbowfish [DRF] swimming along the sidewall

Figure 7 (Right). Dimensionless frequencies of fish tail-beat and characteristic fish speed fluctuations as functions of fish length: Silver perch [SP] and Duboulay's Rainbowfish [DRF] swimming along sidewall

The fish tail-beat frequency data are reported in Figure 7 in a dimensionless form $F \times L/V_x$, where L is the fish total length and V_x is the time-averaged longitudinal velocity at the observation location. The data showed that the fish swam in a relatively narrow interval under the tested conditions [7]. The present results showed some correlation in terms of the fish length:

$$F \times L / V_x = 0.0372 \times L^{0.823} \quad (1)$$

with the fish length L in mm. Equation (1) is compared to experimental data in Figure 7. In Figure 7, the tail-beat frequency data are further compared with the characteristic frequency of the longitudinal fish speed. An example of the latter is illustrated in Figure 5 (Right). The results showed a close agreement indicating that the characteristic fish speed frequency may be used as a proxy of the tail-beat frequency (Fig. 7).

Discussion

Variability in fish swimming speed has some important implication in terms of energy expenditure required to swim against the current over a period of time [14]. Power is required to overcome friction and form drag [17], while additional energy is spent during acceleration phases. The former is proportional to the cube of fish speed relative to the mean fluid motion, while the latter is basically the fish mass time acceleration time relative fish speed. Present results highlighted a number of issues that deserve some discussion. The fish speed fluctuations were systematically smaller than the turbulent velocity fluctuations at the fish location. In turn the fish accelerations were small and the corresponding inertial force was minimal. A number of fish speed records suggested a secondary characteristic frequency, for example about 16 Hz in Figure 5. While the primary frequency is likely to correspond to prolonged aerobic swimming, the secondary frequency might indicate some burst swimming. Visual observations showed indeed a faster tail-beat frequency during sprint swimming. Further investigations could consider the characteristic fish acceleration frequencies.

Conclusion

Physical modelling was conducted in laboratory under controlled flow conditions with the aim to facilitate upstream fish migration by maximising slow flow and recirculation regions suitable to small fish passage. A configuration consisting of rough invert and rough sidewall was investigated. Compared to the smooth boundary configurations, the measurements showed a marked effect of asymmetrical boundary roughness on the distributions of velocity and velocity fluctuations. Observations with small native fish species were conducted systematically. The roughness configuration provided secondary current regions next to the rough sidewall and at the corner between the rough sidewall and channel bed, which were suitable to small fish. A large proportion of fish movements consisted of quasi-stationary motion sub-series close to the sidewall, during which the fish speed fluctuations were substantially smaller than the fluid velocity fluctuations. The findings hinted that fish tended to react predominantly to large vortical structures. The characteristic fish speed frequency represented a solid proxy of the fish tail-beat frequency, e.g. to predict energy consumption rate.

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