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Characterizing low velocity zones around a spoiler baffle for improving fish passage performance

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ABSTRACT: One of the common mitigation measures for increasing fish passage through culverts is the concept of increasing roughness by adding secondary elements, such as artificial baffles. Although field assessments of these baffled culverts have shown an increase in passage performance, specific numbers vary for different baffle sizes and different fish species. This highlights the importance of having an understanding of flow fields and their variation with shape and size of individual baffles for an efficient fish passage solution. Furthermore, we need to better understand the response of different fish species towards these altered flows. In this study, we concentrate on characterizing the flow field downstream of baffles for different baffle lengths. The preliminary results shows that the shorter baffle is likely to produce flow fields more suitable for small-bodied fish species compared to the tested longer baffle.

1 INTRODUCTION

Low-head instream structures, such as culverts, are common hydraulic structures in many rivers. Recent studies have shown a significant effect of these structures on fish migration (Gibson et al., 2005). Flow velocity within these structures often exceeds the swimming capability of fish. The common solution to this problem is to add secondary elements within the wetted perimeter of these structures. These elements create a low-velocity zone (LVZ) within the flow cross-section. The LVZ is the preferred area by fish to travel or to rest after tiring of swimming in higher flow velocity. However, in order to function properly, the size of the LVZ should be big enough to accommodate the target fish species (Boubée et al., 1999). The turbulence within these zones should be minimal or should match with the fish kinematics so that minimum energy is used while travelling (Liao et al., 2003). Since both, the extent and turbulence characteristics of these zones, depend on the shape and size of an individual roughness element, a comprehensive understanding of the flow field and its variation with size and shape of these roughness elements is crucial. This information can subsequently be integrated with fish behaviour to improve the design of fish passage options.

Here, we have considered a spoiler baffle as a representative roughness element. The spoiler baffle is one of the commonly used retrofitted roughness elements in culverts. The common design parameters of these baffles are their dimensions (length, width and height) and the longitudinal and lateral spacing. In New Zealand, two specific sizes of baffles have been recommended (Stevenson et al., 2008). The longer baffle (250 × 120 × 120 mm), also known as a standard baffle, is recommended for culverts with mild slope (< 3 percentage), whereas a shorter baffle (120 × 120 × 120 mm) is recommended for culverts with a steeper slope. The dimension of these baffles is based on the numerical simulation of LVZ downstream of each baffle. Although field tests and numerical simulations have shown an improved flow environment for the standard baffle, no extensive laboratory study on flow hydrodynamics and fish behaviour analysis has been done for these recommended baffles. Existing laboratory results for baffles (Lacey and Rennie, 2011, Larousse et al., 1991) are based on sizes that differ significantly from the ones being recommended in the guideline (Stevenson et al., 2008).

The objective of this study is thus to compare the extent of LVZ in the near wake region downstream of these two baffles. In addition, different turbulent characteristics within this region are assessed. This information is needed for future studies when the behaviour of small-bodied fish species within these regions is studied.

2 EXPERIMENTAL SETUP

Experiments were conducted in an 18-meter long and 0.54-meter wide transparent horizontal flume situated at the Water Engineering Laboratory (WEL) at the University of Auckland. The schematic layout of the flume is shown in Figure 1. Two spoiler baffles of same cross-section (120 × 120 mm) but of different lengths (L_1: 250 mm, L_2: 120 mm) were made of transparent acrylic. These baffles were placed in the centre of the flume, 10.3 metres away from the inlet. The baffles were located sufficiently below the upstream end of the flume to ensure fully developed turbulent flow condition.

The tests were carried out at the bulk average velocity of 0.4 m/s, which is slightly higher than the sustained swimming velocity of 0.3 m/s required for migratory native fish species-specific of New Zealand (Mitchell, 1989). A flow depth of 90 mm was chosen to represent the unsubmerged condition in the shallow flow regime. In order to set up the flow, first, the flume was levelled horizontally and then the flow rate was increased by adjusting the pump rotation (rpm) until the discharge equivalent to the design depth and velocity was obtained. After completing the flow setup, rpm and static depth was noted and was set to these values to reproduce the flow for the remaining measurements.

3 DATA COLLECTION AND PROCESSING

Three-dimensional velocity was measured using an acoustic Doppler velocimeter (ADV) equipped with the side looking probe (Nortek ^{TM} Vectrino^{+}). Measurements were taken at the sampling frequency of 200 Hz for a time period of 3 minutes. The configuration set up was done with a transmit length of 0.3 mm, sample volume height of 2.5 mm and a nominal velocity range of ± 1 m/s. The ADV was installed on a wheeled carriage, which rests on the rail installed at the top of the flume wall. Because of the probe limitation, the top 30 mm portion of flow depth was excluded from measurements. For both the tests, the measurement window extended 240 mm downstream from the leeward face of the baffle, 60 mm at both the sides from the centre of the flume along the transverse direction and 60 mm from the flume bottom in the vertical direction. The data were

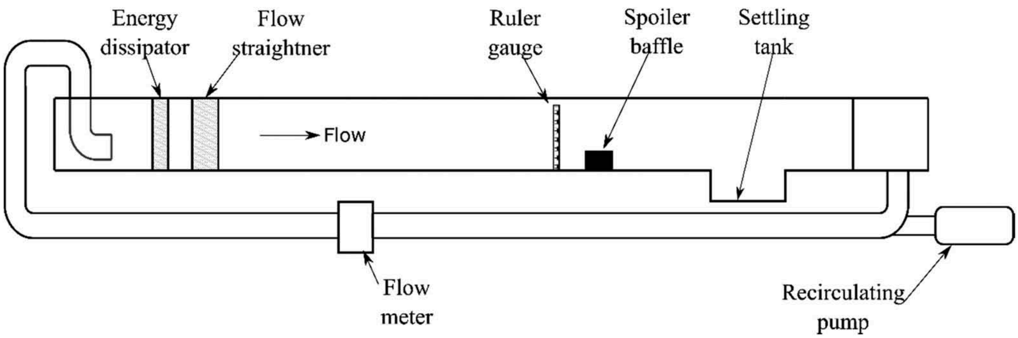

Figure 1. Schematic layout of the 540 flume situated at WEL at the University of Auckland (not to scale).

taken at 30 mm spacing intervals, along the longitudinal and transverse direction, and 10 mm spacing along the vertical direction. The points were located in a Cartesian coordinate system, with X representing streamwise longitudinal direction, positive Y for the lateral distance along the right side of the flume from the centre and the positive Z for the vertical direction from the bottom of the flume. This coordinate system was then normalized (X^+, Y^+, Z^+) by dividing it with the height of the baffle. Similarly, the direction of the velocity component (U, V, W) was assigned as per the right-hand rule with positive streamwise velocity 'U' along the downstream direction.

The measured data were then processed in two stages. It was first filtered based on the signal to noise ratio (SNR) and correlation (COR) value. Any data having SNR less than 15 and COR less than 60 were removed. After completing the first stage, the second stage of processing was done to remove spikes using Goring and Nikora (2002) phase-space threshold algorithm. The total data retained after processing were around 80 % of the total measured data, which is sufficient to analyse various turbulence parameter (Chanson, 2008).

4 RESULTS AND DISCUSSION

Hydrodynamic flow fields downstream of two baffles were compared using mean velocities and turbulence parameters. The preliminary comparison of mean streamwise velocity ($\bar{U}$) downstream of these two baffles shows that the short baffle produces a longer and wider extent of recirculation zones (Figure 2, top), as compared to the long one.

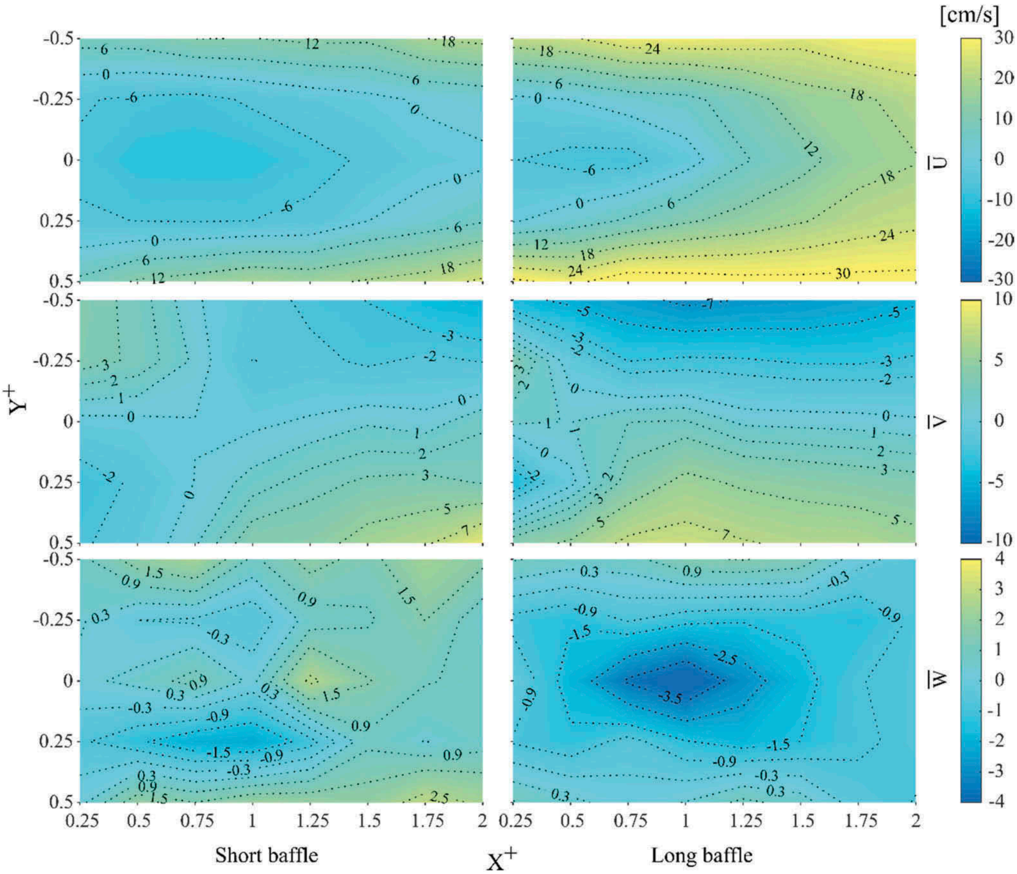

Figure 2. Time averaged velocity U (top), V (middle) and W (bottom) at downstream of long and short baffles (at Z^+=0.33).

The recirculation zone refers to the area with negative streamwise velocity ($\bar{U} < 0$). In the case of a short baffle, this zone extends nearly two baffle heights downstream from its leeward end. Whereas in the case of a long baffle, this length is close to a single baffle height. Similar variations are also seen in the lateral spread, with the recirculation zone in the short baffle being wider than that of the long one.

The alternating positive and negative direction of the mean transverse velocity ($\bar{V}$) shows the vortex shedding phenomena from these baffles (Figure 2, middle). Furthermore, a close comparison shows the variation in transverse velocity gradient along the vortex street between these two baffles specially in the region between $X^+ = 0.5$ to 1.25. In the case of the short baffle, this gradient is much smaller compared to the long baffle. Similarly, comparison of mean vertical velocity also shows a distinct difference between these two baffles (Figure 2, bottom). In the case of the short baffle, two distinct pockets of downward dipping velocity at $Y^+ = +0.25$ and -0.25 exists. These pockets are delineated by a small section of positive upward velocity near the centre and along the edge of the baffle. Whereas in the case of the long baffle, there is strong downward dipping velocity at $X^+ = 1$ along the centre transverse plane.

Similarly, the comparison of various turbulent parameters, mainly Reynolds stresses (Figure 3), turbulent kinetic energy and turbulent intensity (Figure 4) also shows a clear distinction in their distribution downstream of these two baffles. In case of the short baffle, there exists a region immediately downstream of the baffle where the values of these turbulent parameters are significantly lower than that of the long

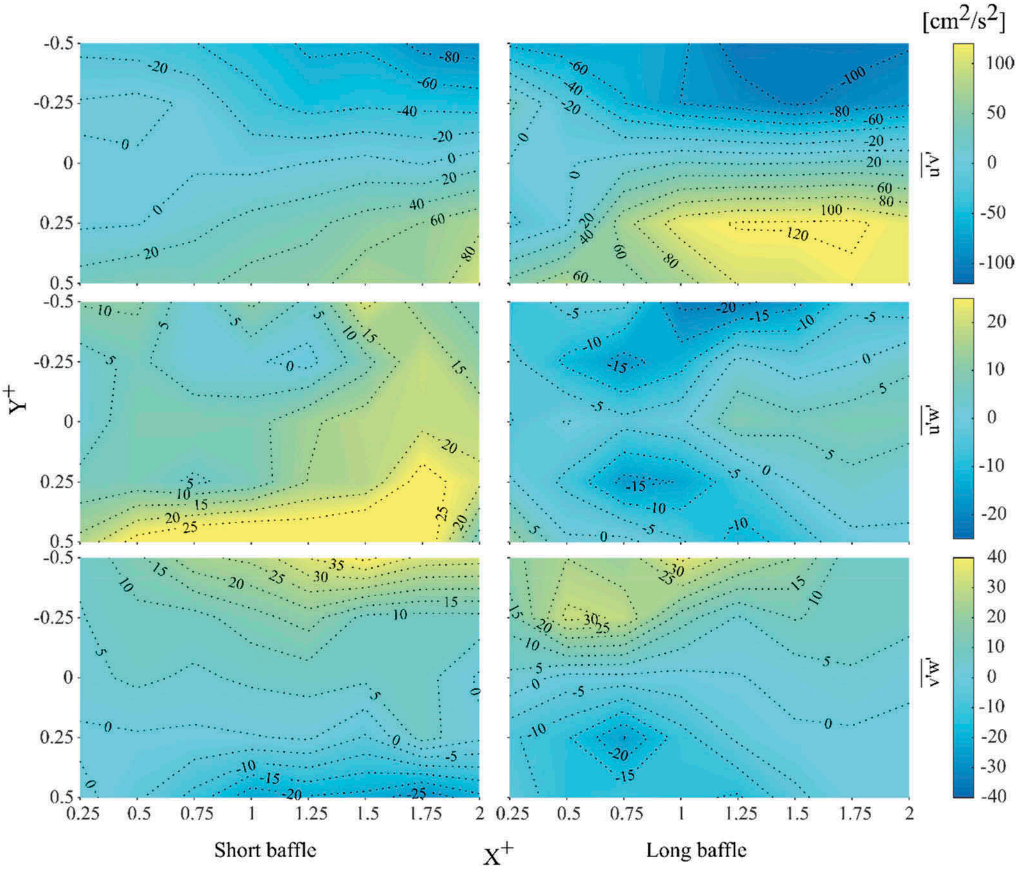

Figure 3. Reynolds stresses downstream of short and long baffle (at Z^+=0.33).

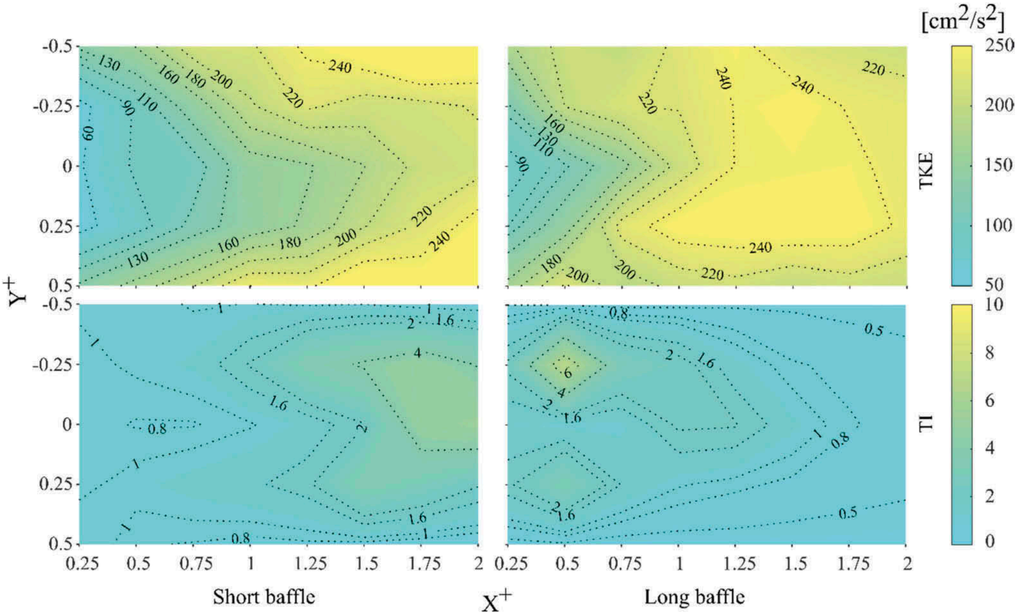

Figure 4. Turbulent kinetic energy (TKE) and turbulent intensity (TI) downstream of short and long baffle (at Z^{+}=0.33).

baffle. Such lower turbulence level and bigger extent of low-velocity zones seem to make shorter baffle more suitable for small-bodied fish species for a flow condition similar to the one used in this study. Although the explicit study on the fish behaviour around the baffle of different size has not been done yet, comparison of few field studies with different baffle size seems to support this result (MacDonald and Davies, 2007, Franklin and Bartels, 2012).

5 CONCLUSION

Despite the fact that spoiler baffles are one of the most widely used fish passage solutions for culverts, little information is available on their hydrodynamic assessment in relation to fish response and behaviour. In this study, we have compared the hydrodynamic flow fields immediately downstream of two baffles. The considered baffle geometries are the ones recommended for culverts in New Zealand. The preliminary comparison of mean flow components and turbulence parameters shows that the short baffle is more likely to generate flow conditions preferable for small-bodied fish species. We recommend an extension of the presented test for different flow conditions to validate the result for broader hydrological conditions. For future work, the next stage of the project will involve the integration of fish behaviour.

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