Jun 28th, 10:30 AM

Baffle Designs to Facilitate Fish Passage in Box Culverts: A Preliminary study

H. Chanson
h.chanson@uq.edu.au

W. Uys

Recommended Citation

Chanson, H., Uys, W. (2016). Baffle Designs to Facilitate Fish Passage in Box Culverts: A Preliminary study. In B. Crookston & B. Tullis (Eds.), Hydraulic Structures and Water System Management. 6th IAHR International Symposium on Hydraulic Structures, Portland, OR, 27-30 June (pp. 312-321). doi:10.15142/T300628160828 (ISBN 978-1-884575-75-4).

6th International Symposium on Hydraulic Structures Portland, Oregon, USA, 27-30 June 2016
Hydraulic Structures and Water System Management
ISBN 978-1-884575-75-4 DOI: 10.15142/T300628160828

Baffle Designs to Facilitate Fish Passage in Box Culverts: A Preliminary Study

H. Chanson[1] and W. Uys[1]
[1]School of Civil Engineering
The University of Queensland
Brisbane QLD 4072
Australia
E-mail: h.chanson@uq.edu.au

ABSTRACT

Waterway culverts and road crossings are very common structures along water systems, ranging from rural roads to national highways and urban drainage networks. Present expertise in environmental hydraulics of culverts is deficient because of the many empirically-based design guidelines, which are sometimes outdated and often inadequate for fish passage. Engineers and biologists need better, more reliable prediction 'tools' during the design stages to compare the bio-engineering performances of a range of design options. In all the cases, the turbulence of the flowing waters must be optimized efficiently to maximize fish migration. This project focused on the development of simple solutions to retrofit existing box culverts, with the aim to maximize slow flow regions suitable for small fish passage and to minimize the afflux increase. Herein, a physical study of a standard box culvert was performed under controlled flow conditions, and six baffle designs were tested. Two baffle configurations presented promising results: the corner baffles and the streamlined diagonal baffles. The streamlined diagonal baffles assisted with the development of a large recirculation region immediately downstream of each baffle, with a moderate increase in afflux for a given discharge. The optimum design appeared to be the corner baffle system. It produced little additional afflux, while creating excellent recirculation both upstream and downstream of each baffle. However, further testing must be conducted to develop quantitative design guidelines and to assess the impact on real fish passage.

Keywords: *Standard box culvert, Small fish passage, Baffles, Physical modelling.*

1. INTRODUCTION

Culverts are road crossings that pass under a roadway embankment to allow a continuous flow of water. Numerous waterway culverts are installed worldwide. Culvert designs are diverse, using various shapes and materials determined by stream width, peak flows, stream gradient, and minimum cost (Chanson 2004). For the past two decades, concerns regarding the ecological impact of culvert crossings have led to changes in their design. Although the overall culvert discharge capacity is based on hydrological and hydraulic engineering considerations, large culvert flow velocities may create a fish passage barrier. In some cases, the environmental impact on fish passage may affect the upstream catchment with adverse impact on the stream ecology because the installation of road crossings can limit the longitudinal connectivity of streams for fish movement (Warren and Pardew 1998, Brigg and Galarowicz 2013).

Common culvert fish passage barriers include excessive vertical drop at the culvert outlet (perched outlet), high velocity or inadequate flow depth within the culvert barrel, excessive turbulence, and debris accumulation at the culvert inlet (Olsen and Tullis 2013). The increased velocities in the barrel can also produce reduced flow depths (potentially inadequate flow depths for fish passage) relative to the culvert size. Higher culvert exit velocities may also increase perched outlet fall heights (fish barrier) with increased scour hole development downstream.

One of the primary ecological concerns regarding culvert crossings is the potential velocity barrier to upstream fish passage resulting from the constriction of the channel. In an effort to minimize the impact of culvert crossings on stream ecology, several jurisdictions have developed guidelines to ensure that their design will allow for the upstream passage of fish. In Canada, these guidelines are based on a number of criteria including average flow velocity and minimum embedment depth (Hunt et al. 2012).

For culvert rehabilitation applications where fish passage may be a concern, baffles installed along the invert may provide a more fish-friendly alternative, provided that adequate culvert discharge capacity is maintained (Olsen and Tullis 2013). Baffles would decrease the flow velocity and increase the water depth for fish passage.

Although culvert type may not have a major role influencing the fish longitudinal movement, a general data trend indicated that box culverts were most effective (Brigg and Galarowicz 2013). The culvert length is another important factor in allowing upstream passage of some fish species. For example, in northeastern Kansas streams, fish movement data supported culvert length as an important factor since the culverts limiting upstream fish passage were the longest culverts in the study (Brigg and Galarowicz 2013). The behavioral response by some fish species to culvert length and flow turbulence could play a role in their swimming ability and culvert passage rate. A recent discussion paper recommended that three-dimensional analysis of culvert flows should be considered to gain an understanding of the turbulence and secondary flow motion (Papanicolaou and Talebbeydokhti 2002). The authors recommended an in-depth examination of the spanwise and vertical velocity distributions as well as turbulent intensities and kinetic energy in view of the importance of these parameters to fish passage.

The critical parameters of a culvert in terms of fish passage are the dimensions of the barrel, including its length and cross-sectional characteristics and the slope. These geometric characteristics, together with the water levels upstream and downstream of the structure, determine the hydraulic behavior of the culvert, i.e. the flow discharge, the head loss through the culvert, the flow pattern, and the turbulent velocity field in the barrel (Henderson 1966, Hee 1969, Chanson 2004). The variability of the culvert dimensions is linked to the characteristics and constraints of the site where the road crossing has to be built, the flow discharge passing through the facility, and the compliance with specifications for volumetric power dissipation. This variability results in a wide diversity in flow patterns that can be observed in existing culverts. These flow patterns are one of the elements determining the capacity of the facility to allow the targeted fish species to pass successfully. Indeed, observations in fishways showed that fish behavior was strongly affected by the turbulent flow and its structure (David et al. 2012).

1.1. Designing a Culvert Fish Pass

The selection of the type of culvert fish pass and of the fish pass characteristics depends on the swimming capacities of the fish species. If the fish swimming power is greater than the maximum volumetric power (Bates 2000), the fish will be able to pass the successive baffles and rest in each pool, thus successfully negotiating a fish pass consisting of a large number of pools without difficulty. Currently, there is no simple technical means for measuring the characteristics of turbulence in a fish pass, although it is acknowledged that the turbulence in a fish pass plays a key role in fish behavior (Liu et al. 2006, Yasuda 2011, Bretón et al. 2013). The key turbulence characteristics, which are deemed most important to migrating fish, have been identified as turbulence intensity, Reynolds stresses, turbulent kinetic energy, vorticity, and dissipation (Pavlov et al. 2000. Hotchkiss 2002, Nikora et al. 2003). Recent observations further showed that fish may take advantage of the unsteady character of the turbulent flow (Wang et al. 2010, Tarrade et al. 2011).

In Australia, national guidelines on fish passage requirements for waterway crossings developed in 2003 were based on limited data for native Australian fish. The biological information that underpinned these recommendations was based on research and evaluation of overseas fish species (e.g., salmonids) that display vastly superior swimming capabilities than most Australian native fish. Currently, Australian national recommendations provide little guidance concerning specific culvert design parameters. They merely indicate that water depth should range between 0.2 to 0.5 m with bulk velocity less than 0.3 m/s during base flows, and the culvert cross-sectional area should maximize geometric similarities of the natural waterway profile (Fairfull and Witheridge 2003), thus yielding uneconomical culvert designs. Newer research suggested that bulk velocity maxima should to be revised down to 0.1 m/s for culvert lengths up to 15 m (Rodgers et al. 2014).

In this paper, the hydraulic testing of a range of baffle designs in a standard box culvert was conducted. Physical modelling was conducted in a laboratory under controlled flow conditions to test a variety of baffle designs, with the aim to minimize the afflux increase and to maximize slow flow and recirculation regions suitable to small fish passage. The project focused on the development of simple solutions to retrofit existing box culverts.

2. EXPERIMENTAL FACILITY AND PHYSICAL MODELLING

2.1. Physical Facility

Physical modeling was conducted in a box culvert model located in the AEB hydraulics laboratory at the University of Queensland (Figure 1). All tests were conducted with clear water and without fish. The model culvert had the following barrel internal dimensions: W = 0.150 m, H = 0.105 m, and L = 0.50 m, where W = width, H = height, L = length of the barrel. The barrel invert was aligned with the upstream and downstream channel bed. The design flow conditions of the model were a design discharge: Q_{des} = 0.010 m^3/s, a tailwater depth at design flow: d_{tw} = 0.038 m, with a corresponding afflux: Δh = 0.087 m. This model was constructed at a scale of 1:7 to 1:20 depending upon the full-scale application.

The model was tested for eight flow rates between Q = 0.001 m^3/s and 0.014 m^3/sec, each with three downstream water depths of 0.020 m, 0.038 m, and 0.045 m. Water was supplied from a constant head tank. The flow rate was measured by a Venturi meter calibrated on site, and the water depths were recorded with a pointer gauge. Visual observation of flow recirculation and flow turbulence was conducted by injecting vegetable blue dye around points of interest. Photographs and video movies were taken to characterize the slow flow motion and recirculation regions.

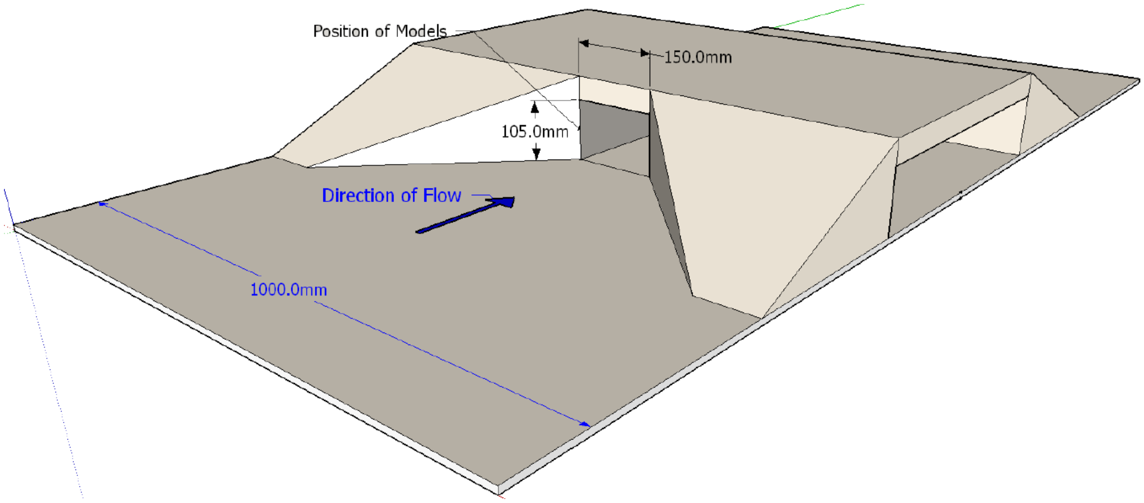


Figure 1. Box culvert model: dimensioned sketch

2.2. Baffle Designs

Six different designs were selected and tested (Figure 2). The corner baffle design and both diagonal baffle designs aimed to generate recirculation in the barrel. The partial pipe system and the rough inverts were designed to reduce the bulk velocity through the culvert barrel. The models were constructed on either a false bottom or a false bottom and sidewall (4 mm thick). This allowed the quick installation and replacement of models, although it is acknowledged that the increase in invert elevation and the narrowing of the barrel caused by the false plates had some impact on the flow.

The corner baffle system (Figure 2e) used the false bottom and side as a base. Triangular baffles were fixed in the bottom left corner of the model to both the false plates. Each triangular baffle was 0.02 m high and wide, and a baffle was positioned every 0.10 m. The most upstream baffle was positioned 0.05 m inside the barrel, and the most downstream baffle was positioned 0.05 m before the barrel outlet.

The partial pipe design (Figure 2b) aimed to slow down the velocity by reducing the hydraulic diameter along the bottom corner. Gaps between rectangular plates were introduced to avoid fish traveling through complete darkness since fish tend to be attracted to regions of light (Bretón et al. 2013). The system was constructed with a false bottom and side. The rectangular plates were 0.05 m by 0.03 m fixed diagonally at 45°. Seven plates were installed, with a gap of 0.025 m between plates. The first plate was fixed with its leading edge in line with the barrel entrance.

The model with diagonal baffles (Figure 2c) consisted of 0.012 m high baffles fixed to a false bottom. The baffles were oriented to 60° with the streamwise flow direction, and they were positioned with a 0.01 m gap between the barrel sidewalls and the baffles. Each baffle was constructed from 0.012m×0.012m aluminium angle, and all were orientated the same way, with 0.10 m longitudinal spacing between baffles. The leading edge of the most upstream baffle was located 0.0125m inside the barrel.

The streamlined diagonal baffle design (Figure 2d) was based upon the diagonal baffles model. 30° ramps were installed upstream of each baffle to reduce the energy loss.

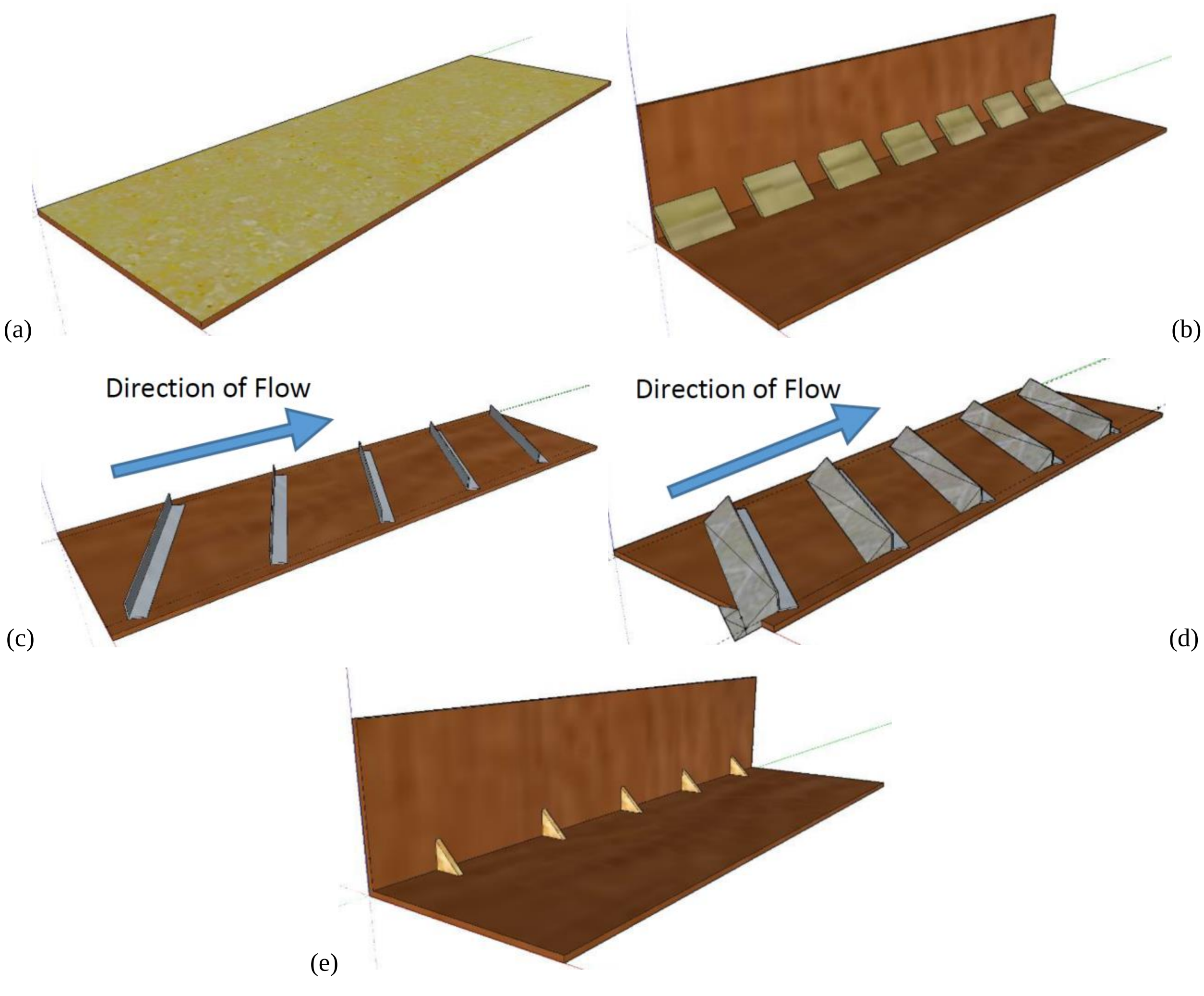


Figure 2. Baffle designs - From top to bottom, left to right: rough sand paper, partial pipe system, diagonal baffles, streamlined diagonal baffles and corner triangular baffles

The last two models used a rough invert (Figure 2a). This aimed to replicate a nature-like stream bed within the barrel. Culverts that had a nature-like invert were thought of as being capable of facilitating fish passage. Each model consisted of a sheet of sandpaper fixed to a false bottom. The first model used grade P40 sandpaper, while the second used grade P60 sandpaper. The rugosity of the sand papers was an average particle size of $k_s = 0.425$ mm and $k_s = 0.269$ mm for the P40 and P60 sandpaper, respectively. (Washington Mills 2015).

3. FLOW PATTERNS AND RECIRCULATIONS

Basic flow patterns were investigated systematically for all discharge and tailwater levels. The followings summarizes the key outcomes.

The rough invert (sand paper) designs slowed the fluid velocity along the surface of the invert. The effect of the P40 sandpaper was greater than that of the P60 sandpaper. In both cases, the effect was restricted to a very thin layer of fluid immediately above the invert (Figure 3, Top). With the partial pipe system, the decrease in velocity did not appear to be significant when compared to the variability in flow velocity within the barrel (Figure 3, 2nd from top). Combined with the lack of flow recirculation, the design was not a practical solution for fish passage.

The diagonal baffle design had different impacts depending upon the discharge. At low flows, the design caused a hydraulic drop immediately downstream of the last baffle, which would be an obstacle for fish passage. At larger flows, the diagonal baffles created regions of helicoidal recirculation (Figure 3, 3rd from top). Although these could act as resting spots for fish, it is unknown whether many fish species could take advantage of such a recirculation motion. Practically, the diagonal baffle system had the potential to cause a debris build-up within the barrel. The effectiveness of the diagonal baffle system was improved by the installation of a ramp in front of each baffle. The ramp reduced the drag caused by a baffle and may reduce the build-up of debris due to the flow streamlining.

The corner baffle design succeeded in creating recirculation eddies. The triangular baffles caused recirculation zones extending both upstream and downstream (Figure 3, Bottom). For the model dimensions, the spacing between baffles allowed the upstream and downstream recirculation zones to connect. The patterns of these recirculation zones were close to those described by Liu et al. (1966). Overall, the corner baffles generated recirculation currents that could allow fish to rest between episodes of burst speed or sustained speed swimming (Baker and Votapka 1990).

4. RELATIONSHIP BETWEEN UPSTREAM WATER LEVEL AND DISCHARGE

For a range of flow conditions, the relationship between upstream water level and discharge was investigated for all six designs and for the (original) un-modified box culvert. Figure 4A presents the results for the original box culvert, with the thick blue line highlighting the design flow conditions. The culvert performed under inlet control for flow rates including and above $Q = 0.0035$ m^3/s. At low flow rates, the culvert operated as outlet control. That is, the upstream water height was a function of tailwater depth. The box culvert was also tested with a false bottom model and a false bottom and side model without any baffle. The differences were small to negligible compared to the (original) un-modified box culvert (see for example Figure 5).

For all baffle design configurations, the relationship between headwater level and discharge was tested. Typical results are presented in Figure 4B. The rough sand paper invert designs, corner baffle design, and partial pipe design yielded the smallest increase in afflux for a given discharge and tailwater level. The largest increase in afflux was observed with the diagonal baffle design for all flow conditions, with an increase in afflux of 0.01 m to 0.02 m (Figure 4B). The streamlined diagonal baffle design yielded intermediate results.

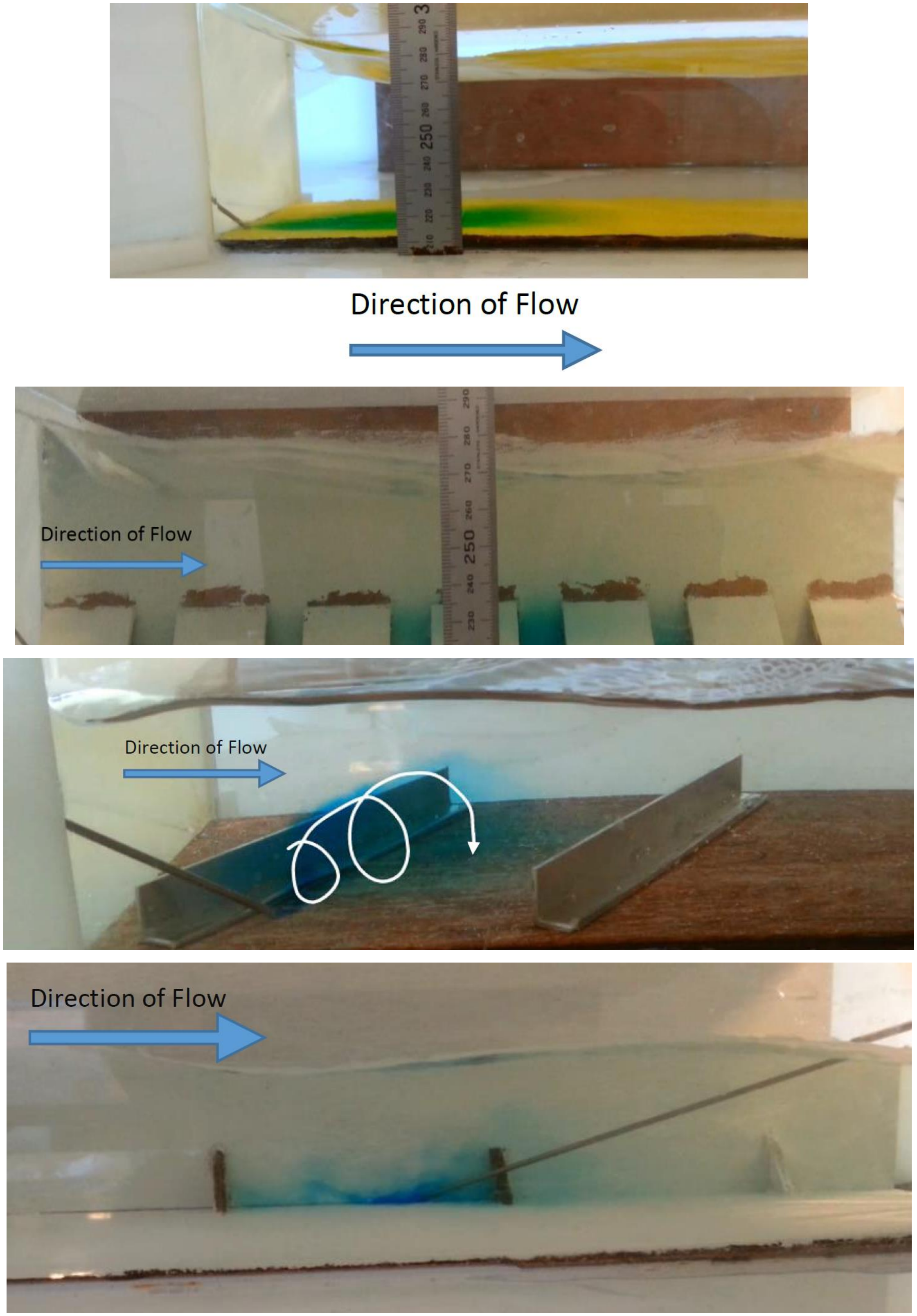
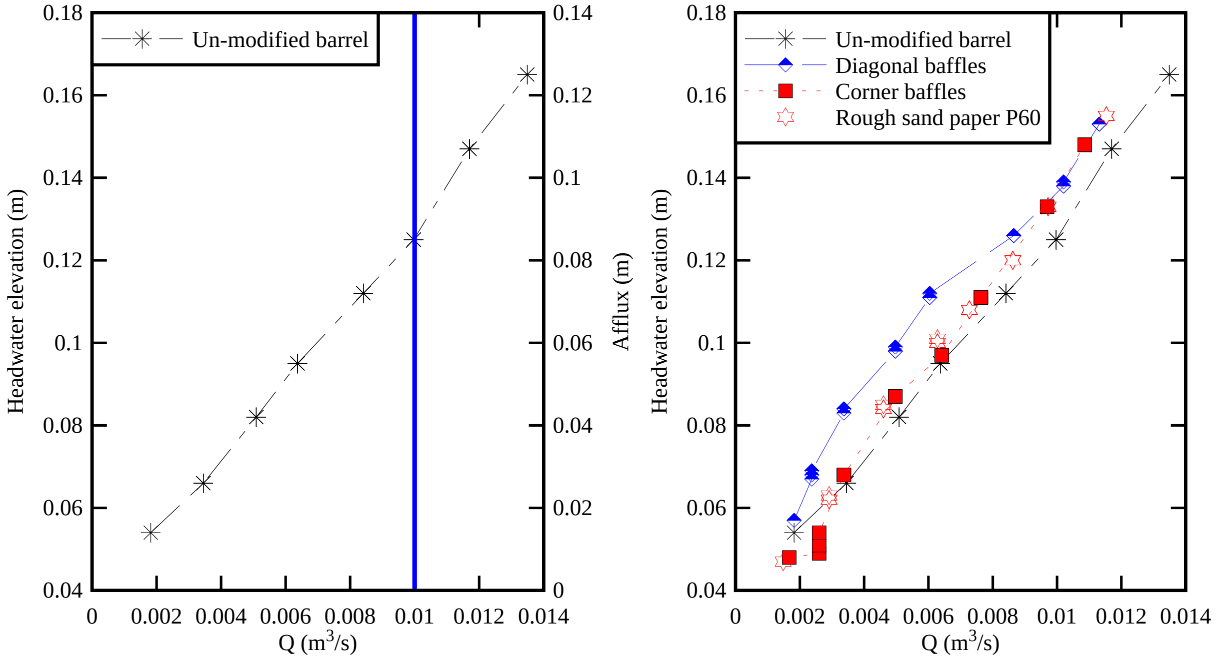


Figure 3. Photographs of slow flow and recirculation regions in the culvert barrel highlighted using dye injection - Flow direction from left to right



(A, Left) Original, un-modified box culvert - Solid blue line: design discharge

(B, Right) Box culvert equipped with baffle designs

Figure 4. Relationship between upstream water depth and discharge

5. DISCUSSION

With the diagonal baffle design, two different flow regimes were present within the barrel for flow rates larger than Q = 0.00935 m^3/s: drowned conditions and un-drowned conditions (Figure 6). Figure 6A presents an un-drowned flow motion and Figure 6B a drowned flow condition (flow from left to right). The barrel was un-drowned at small flow rates. When the flow rate increased slowly, the barrel changed flow regimes into drowned conditions (Fig. 6B). In order to retain the initial un-drowned condition, the flow rate needed to increase relatively rapidly to the new flow conditions (Figure 6A). In practice, the transition between the two states of barrel flow might be abrupt as discussed by Montes (1997) and might lead to large pressure and pressure fluctuations on the obvert, which should be avoided.

Interestingly, the afflux Δh was smaller under drowned conditions for a given discharge $Q > 0.00935$ m^3/s (Fig. 5). This is illustrated in Figure 5 where the upstream water level is presented as a function of the discharge, the drowned flow conditions being shown with red colored symbols. The lower value for afflux, developed from the drowned barrel conditions, should not be used to design box culverts with diagonal baffles, however. The results were unrelated to the tailwater level, within $0.020 < d_{tw} < 0.045$ m.

Lastly, the present laboratory experiments were conducted for Reynolds numbers ranging from 3×10^4 to 1×10^5. The laboratory flow conditions corresponded to turbulent flows, in line with the literature recommending that the physical model flows be turbulent, with the same relative roughness as for the prototype (Novak and Cabelka 1981, Hughes 1993, Chanson 2004). Any extrapolation of the results to full-scale must, however, be conducted with care, and full-scale testing should be considered.

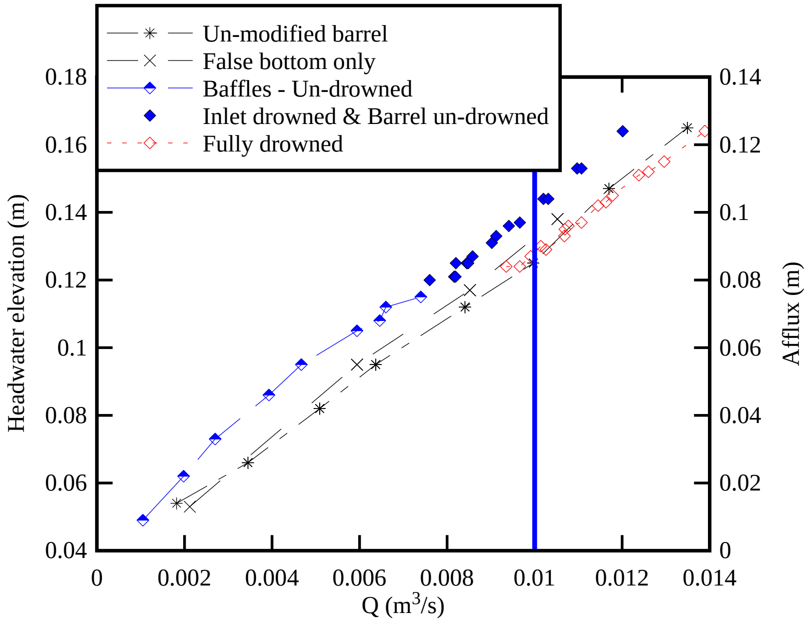
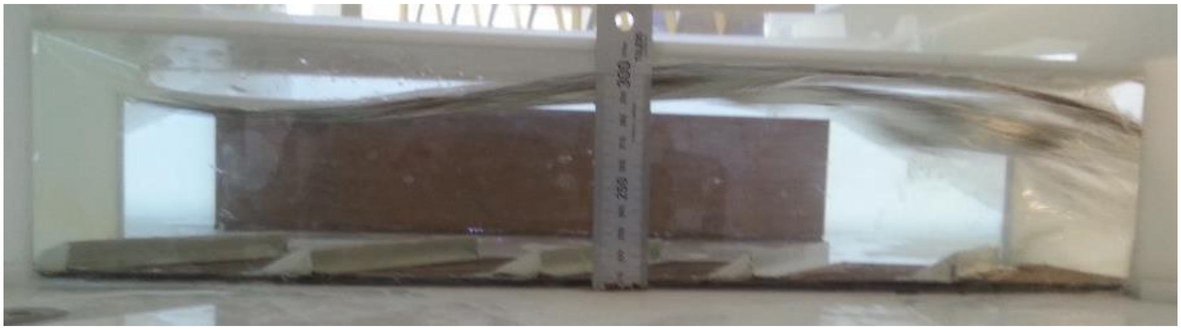
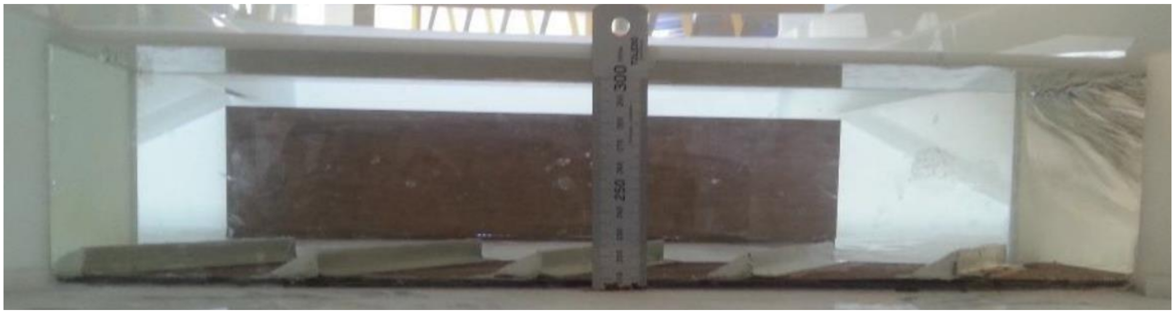


Figure 5. Relationship between upstream water depth and discharge for diagonal baffle design: effect of barrel flow conditions - Thick blue line: design discharge



(A) Un-drowned barrel flow conditions for $Q = 0.012$ m^3/s, $\Delta h = 0.126$ m



(B) Drowned barrel flow conditions for $Q = 0.0139$ m^3/s, $\Delta h = 0.126$ m

Figure 6. Operation of box culvert with diagonal baffle design at large discharges - Flow direction from left to right

6. CONCLUSION

Physical modelling of a standard box culvert was performed with a range of baffle designs. The study aimed to minimize the increase in afflux and to maximize slow flow and recirculation regions, which might facilitate the passage of fish with small body mass, upstream migration in particular. A total of six configurations plus the un-modified box culvert were tested.

Two baffle configurations presented promising results: the corner baffle design and the streamlined diagonal baffle design. The streamlined diagonal baffles assisted with the development of a large recirculation region immediately downstream of each baffle, with a moderate increase in afflux for a given discharge. However, it should not be used until further investigation is conducted on both fish behavior in the helicoidal recirculation and development of drowned conditions. Overall, and based upon physical modelling, the optimum design appeared to be the corner baffle system. It produced little additional afflux while creating excellent recirculation regions both upstream and downstream of each baffle, which might be suitable to small fish typical of Australian streams.

It must be acknowledged that the present findings are preliminary. Further design testing must be conducted to develop quantitative design guidelines with optimum baffle dimensions and spacing. Tests must further encompass impact on real fish passage: that is, in a laboratory using fish-friendly facilities and complemented by field monitoring of prototype structures.

7. ACKNOWLEDGMENTS

The authors acknowledge the technical assistance of Jason Van Der Gevel and Stewart Matthews (The University of Queensland). HC acknowledges helpful discussions with UQ Biological Sciences and NSW Department of Fisheries colleagues and the input of Dr Hang Wang (The University of Queensland). The financial support through the Australian Research Council (Grant LP140100225) is acknowledged.

8. REFERENCES

Baker, C.O., and Votapka, F.E. (1990). Fish passage through culverts. Dept. of Transportation, Federal Highway Administration, United States Department of Agriculture, Forest Service, Washington, D.C., USA.

Bates. K. (2000). Fishway guidelines for Washington State. Washington Department of Fish and Wildlife, 57 pages.

Bretón, F., Baki, A.B.M., Link, O., Zhu, D.Z., and Rajaratnam, N. (2013). Flow in nature-like fishway and its relation to fish behaviour. *Canadian Journal of Civil Engineering*, Vol. 40, No. 6, pp. 567-573(DOI: 10.1139/cjce-2012-0311).

Briggs, A.S., and Galarowicz, T.L. (2013). Fish Passage through Culverts in Central Michigan Warmwater Streams. *North American Journal of Fisheries Management*, Vol. 33, No. 3, pp. 652-664 (DOI: 10.1080/02755947.2013.788589).

Chanson, H. (2004). The Hydraulics of Open Channel Flow: An Introduction. Butterworth-Heinemann, 2nd edition, Oxford, UK, 630 pages.

Fairfull, S., and Witheridge, G. (2003). Why do fish need to cross the road? Fish passage requirements for waterway crossings. NSW Fisheries, Cronulla NSW, Australia, 14 pages.

David, L., Calluaud, D., Pineau, G., and Texier, A. (2012). Fishway Hydrodynamics and Global Approaches for insuring the Upstream Migration around Dams. *Proc. 4th IAHR International Symposium on Hydraulic Structures*, APRH - Associação Portuguesa dos Recursos Hídricos (Portuguese Water Resources Association), J. Matos, S. Pagliara & I. Meireles Editors, 9-11 February 2012, Porto, Portugal, Paper 4, 15 pages (CD-ROM).

Hee, M. (1969). Hydraulics of Culvert Design Including Constant Energy Concept. *Proc. 20th Conf. of Local Authority Engineers*, Dept. of Local Govt, Queensland, Australia, paper 9, pp. 1-27.

Henderson, F.M. (1966). Open Channel Flow. MacMillan Company, New York, USA.

Hotchkiss, R. (2002). Turbulence investigation and reproduction for assisting downstream migrating juvenile salmonids, Part I. BPA Report DOE/BP-00004633-I, Bonneville Power administration, Portland, Oregon, 138 pages.

Hughes, S.A. (1993). Physical Models and Laboratory Techniques in Coastal Engineering. Advanced Series on Ocean Engineering, Vol. 7, World Scientific Publ., Singapore, 568 pages.

Hunt, M., Clark, S., and Tkach, R. (2012). Velocity distributions near the inlet of corrugated steel pipe culverts. *Canadian Journal of Civil Engineering*, Vol. 39, No. 12, pp. 1243-1251 (DOI: 10.1139/l2012-112).

Liu, C.K., Kline, S.J., and Johnston, J.P. (1966). An Experimental Study of Turbulent Boundary Layer on Rough Walls. Report ND-15, Stanford University, Dept of Mechanical Engineering, 171 pages.

Liu, M.M., Rajaratnam, N., and Zhu, D,Z. (2006). Mean flow and turbulence structure in vertical slot fishways. *Journal of Hydraulic Engineering*, ASCE, Vol. 139, No. 4, pp. 424-432.

Montes, J.S. (1997). Transition to a Free-Surface Flow at End of a Horizontal Conduit. Journal of Hydraulic Research, IAHR, Vol. 35, No. 2, pp. 225-241.

Nikora, V., Aberle, J., Biggs, B., Jowett, I., and Sykes, J. (2003). Effects of fish size, time-to-fatigue and turbulence on swimming performance: a case study of Galaxias maculatus. *Journal of Fish Biology*, Vol. 63, pp. 1365-1382.

Novak, P., and Cabelka, J. (1981). Models in Hydraulic Engineering. Physical Principles and Design Applications. Pitman Publ., London, UK, 459 pages.

Olsen, A.H., and Tullis, B.P. (2013). Laboratory Study of Fish Passage and Discharge Capacity in Slip- Lined, Baffled Culverts. *Journal of Hydraulic Engineering*, Vol. 139, No. 4, pp. 424-432 (DOI: 10.1061/(ASCE)HY.1943-7900.0000697).

Papanicolaou, A.N., and Talebbeydokhti, N. (2002). Discussion of Turbulent open-channel flow in circular corrugated culverts. *Journal of Hydraulic Engineering*, Vol. 128, No. 5, pp. 548–549.

Pavlov, D.S., Lupandin, I.A., and Skorobogatov, M.A. (2000). The effects of flow turbulence on the behavior and distribution of fish. *Jl Ichthyol*, Vol. 40, pp. S232–S261.

Rodgers, E.M., Cramp, R.L., Gordos, M., Weier, A., Fairfall, S., Riches, M., and Franklin, C.E. (2014). Facilitating upstream passage of small-bodied fishes: linking the thermal dependence of swimming ability to culvert design. *Marine and Freshwater Research*, Vol. 65, pp. 710-719 (DOI: 10.1071/MF13170).

Tarrade, L., Manceau, R., Texier, A., David, L., and Larinier, M. (2005). Etude numérique des écoulements hydrodynamiques turbulents dans une passe à poissons. *Proceedings of the 17ème Congrès Français de Mécanique*, Troyes, France, 6 pages (in French).

Wang, R.W., David, L., and Larinier, M. (2010). Contribution of experimental fluid mechanics to the design of vertical slot fish passes. *Knowledge and Management of Aquatic Ecosystems*, Vol. 396, No. 2, 21 pages (DOI: 10.1051/kmae/2010002).

Warren, M.L., Jr., and Pardew, M.G. (1998). Road crossings as barriers to small-stream fish movement. *Transactions of the American Fisheries Society*, Vol. 127, pp. 637–644.

Washington Mills. (2015). Particle Size Conversion Chart - ANSI. <http://www.washingtonmills.com/guides/grit-sizes-ansi/particle-size-conversion-chart-ansi/> (Retrieved 5th June, 2015).

Yasuda, Y. (2011). Guideline of Fishway for Engineers. Corona Publishing, NPO Society for Fishway in Hokkaido, Japan, 154 pages (in Japanese).