Using Particle Image Velocimetry (PIV) System in Fish Passage Through Rehabilitated Culverts

Mohanad Khodier
Blake P. Tullis
Utah State University, blake.tullis@usu.edu
USING PARTICLE IMAGE VELOCIMETRY (PIV) SYSTEM IN FISH PASSAGE THROUGH REHABILITATED CULVERTS

Mohanad KHODIER
Civil and Environmental Engineering, Utah State University, USA,
m.khodier@aggiemail.usu.edu
Blake P. TULLIS
Civil and Environmental Engineering, Utah Water Research Laboratory, USA,
blake.tullis@usu.edu

ABSTRACT: The Particle Image Velocimetry (PIV) system was used to investigate fish passage behaviour through a circular, 0.61-m diameter pipe with evenly spaced baffles along the invert. A section of the pipe wall between two adjacent baffles was replaced with a transparent window (Lexan) and a water box placed outside of the pipe to create a tested section. The test was conducted for different pipe slopes 0.5, 1.5, 2.5, and 3.5%. For each slope, the pipe was tested for different flow rates 28.3, 56.6, and 85 l/s. Also, the PIV was used to produce the velocity vector field by post-processing the particle images. Using the measured velocity field data, the velocity gradient (shear stress) was calculated for the entire field downstream of the baffle. The velocity gradients will be used to better understand the effect that installing baffles has on fish passage. Live fish were placed in the pipe under the same slope and discharge conditions and their behaviour observed, including favorite resting places. The flow characteristics near the fish resting places were also evaluated.

Keywords: PIV, fish passage, rehabilitated culverts, pipe baffles.

INTRODUCTION

Culverts are used to convey water flows from one side of a road to the other. One concern about using culverts is the ability for fish to move upstream through the culverts. One way to increase fish passage ability is to install baffles within the culverts along the invert. Baffles are elements built inside the culverts with regular spacing and specific height. Baffles decrease the flow velocity and increase the water depth for the fish passage by creating pools of slower water where the fish can rest (Rajaratnam and Katopodis, 1990). Rajaratnam tested multiple types of baffled culverts included slotted weir, offset, and weir baffles to compare their performance on fish passage. All baffles types had the same results for the fish passage.

Other studies were conducted on culvert slopes ranging from 1% to 5% (Rajaratnam and
Katopodis, 1990). Morris (1968) studied the effect of baffle height and the spacing length between baffles. Morris concluded that the baffle spacing to baffle height ratio should be between 8.5 and 10 for fish passage. Olsen and Tullis (2011) conducted multiple tests on baffled and non-baffled culverts at seven slopes (0–3.5%) and three flow rate for each slope. Olsen and Tullis (2011) concluded that the slope of the non-baffled culvert should be less than 0.5% with a flow rate of 28.3 l/s to have 50% of fish pass (specifically brown trout). The same percentage of the fish passing can be achieved with a slope of 3.5% and 28.3 l/s flow with a baffled culvert. In this study, the effect of shear stress and velocity gradient on fish passage in a baffled culvert was explored.

**EXPERIMENTAL SETUP**

Flow through a 18.3-m long, 0.61-m outer diameter baffled pipe was tested using the PIV system (Figure 1). The pipe was made from high-density polyethylene, HDPE. The wall thickness of the pipe was 19 mm, the baffle spacing was 0.9D, and the baffles height was 0.15D, where D is the inner diameter of the pipe (Figure 1).

![Figure 1 – Experimental setup](image)

The upstream end of the pipe was connected to the supply tank, and the downstream end was opened to the atmosphere for discharging into a drainage system. A test section was placed at the middle of the pipe between two adjacent baffles. This test section consisted of a transparent 0.36-m wide by 0.4-m tall window made from a 3-mm thick flexible Lexan sheet that matched the pipe wall curvature (see Figure 2). In order to eliminate the distortion of the image through the curved window, a clear acrylic 0.58×0.69×0.64-m water box was placed on the outside of the pipe at the test section (see Figure 3). Laser light reflection off of the water free surface can also create imaging problems for the PIV system. To overcome this problem, a very thin black sheet (cloth) was placed at the top of the water surface to absorb the laser light. The sheet was buoyant and very lightweight so as not to significantly impact the flow geometry. The PIV system consisted of a CCD camera with 1280×1024 pixels resolution and a laser (Nd:YAG) with...
light sheet optics to illuminate the desired area (see Figure 2). The PIV system was used to measure the velocity field and subsequently calculated the flow shear stresses.

![Image of PIV system and test section](image1)

**Figure 2** – PIV system and the test section

![Image of PIV system and attached box](image2)

**Figure 3** – PIV system and the attached box

**RESULTS AND DISCUSSION**

Multiple flow tests were conducted at the following pipe slopes: $S = 0.5, 1.5, 2.5, \text{ and } 3.5\%$ at flow rates of $Q = 28.3, 56.6, \text{ and } 85.0 \text{ l/s}$. The PIV system was used to produce the velocity and the vector field by post-processing the 100 flow field images. The shear stress is given by the following equation:
\[ \tau = \mu \frac{\partial U}{\partial y} \]  

(1)

where \( \tau \) is the shear stress (N/m\(^2\)) and \( \mu \) is the dynamic viscosity (N m/s\(^2\)). It can be noted from this equation that the shear stress is proportional to the velocity gradient. Figure 4 shows the velocity contour for the space between the baffles at \( S=0.5\% \) and \( Q=85.0 \text{ l/s} \). The baffle height was at \( y = 85.75 \text{ mm} \) from the pipe invert. The space between the baffles produced a low velocity field that allowed the fish to rest during the passage (see Figure 4).

![Figure 4 – Velocity contour for U (m/s) at S=0.5% and Q=85 l/s (T=6.4°C)](image)

It is noted that the space between the baffles reduced the velocity (kinetic energy) and creates an eddy with clock-wise oriented flow (see Figure 5). Figure 5 shows the velocity vector and the eddy direction for the space between the baffles only.
In a typical flow through a pipe, the velocity gradient (shear stress) is maximum near the wall and reduced towards the center of the pipe. Installing baffles in the pipe will change this behaviour, as shown in Figure 6. The velocity gradient (shear stress) is minimum near the wall and increases toward the top of the baffles (at \( y = 85.75 \text{ mm} \)), where the velocity gradient is highest, and then decreases again with increased elevation in the water column. This behaviour is also true for different flow rates and slopes as shown in Figures 7, 8, and 9. It can be noted from these figures that the velocity gradient converges to a certain value (less than the maximum velocity gradient) as the flow goes downstream of the space between the baffles.

The downstream is the upstream for the next baffle space, so fish jumping from one space to the next space will not suffer from the high velocity gradient. Figure 10 shows the location of the maximum velocity gradient for different flow rates. As the flow rate increases, the maximum velocity gradient increases. It can be noted from this figure that the maximum velocity gradient is located near the top of the baffles (at \( y = 85.75 \text{ mm} \)).
Figure 6 – Velocity gradient for $S=0.5\%$ and $Q=28.3\ l/s\ (T=6.4^\circ C)$

Figure 7 – Velocity gradient for $S=0.5\%$ and $Q=85.0\ l/s\ (T=6.4^\circ C)$
Figure 8 – Velocity gradient for $S=3.5\%$ and $Q=56.6$ l/s ($T=5.6\, ^{\circ}C$)

Figure 9 – Velocity gradient for $S=3.5\%$ and $Q=85.0$ l/s ($T=5.6\, ^{\circ}C$)
CONCLUSION

The PIV System was used to investigate the fish passage behaviour through a circular pipe. The 18.3-m long and 0.61-m outer diameter baffled pipe was tested at different geometrical slopes: 0.5, 1.5, 2.5, and 3.5%. For each pipe slope, the pipe was tested for different flow rates: 28.3, 56.6, and 85.0 l/s. The velocity and vector field were produced by post-processing the particle images. The velocity gradient (shear stress) is calculated for each flow and geometry condition. It can be concluded that installing baffles in the pipe will reduce the velocity and the velocity gradient in the space between the baffles, which makes a good environment for the fish to rest during passage in the pipe. The baffles will shift the maximum velocity gradient from the pipe wall to the top of the baffles. The velocity gradient increases as the slope increases. Also, the velocity gradient increases as the flow rate increases. Regardless of the slope and the flow rate, the velocity gradient converges downstream of the baffles spacing, where it has the approximately a small velocity gradient. In future studies, the fish will be monitored during passage through the baffled pipe to determine the place where fish most often rest.

ACKNOWLEDGMENTS

I would like to thank Utah Department of Transportation that funds this project. Special thanks to Dr. Blake Tullis for his guidance and support. Also, I would like to thank Ricky Anderson for building the experimental set up. Special thanks to Zac Sharp for his technical support and Dr. Barton Smith for his guidance.

IJREWHS ’12 63 Khodier
REFERENCES


