An Analysis of Partial-Depth, Floating, Impermeable Guidance Structures for Downstream Fish Passage at Hydroelectric Facilities

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AN ANALYSIS OF PARTIAL-DEPTH, FLOATING, IMPERMEABLE GUIDANCE STRUCTURES FOR DOWNSTREAM FISH PASSAGE AT HYDROELECTRIC FACILITIES

A Dissertation Presented

by

KEVIN MULLIGAN

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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Environmental and Water Resources Engineering, Department of Civil and Environmental Engineering
AN ANALYSIS OF PARTIAL-DEPTH, FLOATING, IMPERMEABLE GUIDANCE STRUCTURES FOR DOWNSTREAM FISH PASSAGE AT HYDROELECTRIC FACILITIES

A Dissertation Presented
by
KEVIN MULLIGAN

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DEDICATION

To my late grandparents, Mario and Mary Silva,

and my late grandaunt, Laurinda Figueiredo.
ACKNOWLEDGMENTS

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ABSTRACT

AN ANALYSIS OF PARTIAL-DEPTH, FLOATING, IMPERMEABLE GUIDANCE STRUCTURES FOR DOWNSTREAM FISH PASSAGE AT HYDROELECTRIC FACILITIES

SEPTEMBER 2015

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Partial-depth, impermeable guidance structures (or guide walls) are used to enhance downstream passage effectiveness at a hydroelectric facility by actively guiding fish to a safe passage route (i.e. the bypass). Guide walls have been installed in a variety of ways and, like many fish passage devices, have resulted in variable efficiency rates. Currently, the most common type of installment is a steel panel guide wall attached to a floating boom. While less utilized than other guidance structure options (e.g. louvers and bar racks), guide walls have been gaining popularity, particularly within the Northwest United States.

The aim of this dissertation is to perform a literature review on guide walls and to provide a detailed assessment on how the key design parameters of a guide wall impact the flow field. Chapter 1 is broken into two sections. First, a literature review is performed on guide walls, explaining the history of their use and their effectiveness. Second, a computational fluid dynamics (CFD) model is developed and used to evaluate the effect of several guide wall design parameters (depth, angle, and approach flow velocity). Chapter 2 provides another analysis of the hydraulic conditions upstream of a
guide wall, but does so using a lab-scale model. The results of Chapter 1 are compared to that of Chapter 2. Lastly, Chapter 3 performs a sensitivity analysis by evaluating the effect of the bypass flow percentage on the key metric (the ratio of the vertical velocity component to the sweeping velocity magnitude) developed in Chapter 1 & 2.

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CHAPTER 1

A REVIEW OF PARTIAL-DEPTH, IMPERMEABLE GUIDANCE STRUCTURES FOR DOWNSTREAM FISH PASSAGE AND HOW THEIR DESIGN PARAMETERS AFFECT THE FLOW FIELD

1.1 Abstract

A partial-depth, impermeable guidance structure (or guide wall) for downstream fish passage is constructed as a series of partial-depth panels anchored across a river channel, reservoir, or power canal. If guidance is successful, the fish will avoid entrainment in a dangerous intake structure (i.e. turbine intakes) while passing from the headpond to the tailwater of a hydroelectric facility through a safer passage route (i.e. the bypass). To evaluate the flow field immediately upstream of a guide wall, a parameterized computational fluid dynamics (CFD) model of an idealized power canal was constructed in © ANSYS Fluent v 14.5 (ANSYS Inc., 2012). The design parameters investigated were the angle and depth of the guide wall and the average approach velocity in the power canal. Results call attention to the importance of the downward to sweeping flow ratio and demonstrate how a change in guide wall depth and angle can affect this important hydraulic cue to out-migrating fish. The key findings indicate that a guide wall set at a small angle ($15^\circ$ is the minimum in this study) and deep enough such that sweeping flow dominant conditions prevail within the expected vertical distribution of fish approaching the structure will produce hydraulic conditions that are more likely to result in effective passage.
1.2 Introduction

Many fish species have evolved to use different types of environments over their life span in order to enhance the population’s chance of survival. Each selected environment is well suited for a particular part of the life cycle for the fish. For instance, anadromous clupeids (genus *Alosa*) are born in a fresh water river system where there are fewer predators, migrate as juveniles to the ocean where there is a more abundant food supply, then migrate as adults back to the fresh water river to spawn, completing the life cycle. In addition, potamodromous fish perform migrations for the purposes of both feeding and spawning, but only within fresh water river systems. Without the ability to freely move between and within each aquatic ecosystem, the chance of a fish population’s long-term survival is greatly diminished (Limburg and Waldman, 2009; McDowall, 1987).

As a result of anthropogenic development on river systems, full and partial barriers to fish movement commonly exist in watersheds worldwide (Williams et al., 2012). These barriers typically consist of small to large size dams, culverts, and other structures. Passage of fish both up and downstream of dams can be difficult to impossible. Even if a fishway structure is in place, poor design, predation, and degraded water quality can lead to fatigue, injury, fatality, or other hindrances to fish survival.

Enhancement of downstream passage efficiencies at hydropower facilities is required on a global scale to meet the clear biological need for fish migration through rivers. Improvements to guidance technologies (e.g., louvers, racks, screens, perforate plates, guide walls) that lead to bypasses (a safe passage route) may prove a more cost-effective way (in comparison to costly collection systems and the curtailment of
hydropower generation due to increased spill) to protect these increasingly important and threatened fish.

Guidance technologies rely on the rheotactic response of fish, among other factors, to improve downstream passage efficiency and reduce migration delay. Rheotaxis is defined as a fish’s behavioral orientation to the water current (Montgomery et al., 1997). A fish’s movement with (or against) the water current is referred to as a negative (or positive) rheotaxis, respectively. In the case of a full-depth guidance structure (e.g. louvers and angled bar racks), the vertical velocity component upstream of the guidance structure is ignored and a 2-dimensional velocity vector is often used to inform the design. These two velocity components are referred to as the sweeping velocity (velocity component parallel to the guidance structure pointing in the direction of the bypass) and the normal velocity (velocity component perpendicular to the guidance structure pointing directly at the face of the structure). A guidance structure installed at 45 degrees or less to the upstream flow field will result in a sweeping velocity greater than or equal to the normal velocity, thereby reducing the likelihood of impingement and entrainment. For this reason, guidance technologies are typically set at a maximum angle of 45 degrees to the flow field, thus creating a hydraulic cue designed to elicit a negative rheotactic response from migrating fish (encouraging their movement downstream towards the bypass).

In the case of a partial-depth guide wall, a strong downward vertical velocity component may be present upstream of the wall. The vertical velocity component may compete with, or even overwhelm, hydraulic cues created by the sweeping and normal velocities. Dominant vertical velocities may encourage vertical fish movement and
exacerbate entrainment potential. The aim of this paper is to review the history of partial-depth guide walls and to provide a detailed assessment on how the structure’s design parameters impact the flow field upstream of the wall. In particular, the analysis focuses on how the ratio of the vertical (or downward) velocity component to the sweeping velocity magnitude changes upstream of a guide wall for different combinations of key design parameters (i.e. depth and angle).

1.3 Background

At a typical hydropower facility there are three primary routes of downstream passage for a fish. The three routes, ordered by typical proportion of average annual river flow, are 1) through the turbine intakes, 2) over a spillway and 3) through a fish bypass (often constructed as a sluice gate, weir, or pipe). The downstream bypass is constructed in close proximity to the turbine intakes to reduce the number of fish passing through the turbines. The challenge is to either induce behaviorally or actively guide the fish into the bypass rather than the turbine intakes, which the bulk of the flow in the power canal passes through (typically >90% when there is no spilling over the dam). Surface guidance technologies, and in particular guide walls, are used for this purpose.

Johnson and Dauble (2006) classified the flow upstream of a typical hydroelectric facility as consisting of three separate zones. The first zone an out-migrating fish will enter is the “Approach Zone”, located about 100-10,000 meters upstream of the dam. Here salmonid and alosine juveniles are expected to follow the bulk flow while remaining in the upper portion of the water column (Whitney et al., 1997; Buckley and Kynard, 1985; Faber et al., 2011). Key features within this zone include channel depth,
channel shape, discharge, shoreline features, and current pattern. The fish movement typically includes both actively swimming and passively drifting.

Next is the “Discovery Zone”, located about 10-100 meters from the dam, where the fish are expected to encounter the flow field of the surface bypass and turbine intakes. Key features here include the forebay bathymetry, structures, velocity gradients (from spill and turbine loading), sound, and light. In this zone, the fish begin to respond to the site specific conditions of the hydroelectric facility. Johnson et al. (2005) showed that the horizontal distribution for juvenile salmonids can be impacted by dam operations in this zone and Venditti et al. (2000) showed that fish tend to spend more time in this zone than they would normally.

Next is the “Decision Zone”, located about 1-10 meters from the dam. Key features here that impact fish behavior are velocity, acceleration, turbulence, sound, light, structures, other fish (Larinier, 1998), and total hydraulic strain (Nestler et al., 2008). Within this zone, the turbine intakes create a strong downward flow component and the surface bypass can bring about strong acceleration. As evidenced by Haro et al. (1998), Kemp et al. (2005), Johnson et al. (2000), and Taft (2000), several juvenile fish species prefer to avoid regions of high acceleration. It is imperative that the fish be entrained in the flow field of the bypass before any of these features stimulate an avoidance reaction and that the hydraulic conditions through the bypass is safe for the fish to travel. It is the goal of the guide wall to alter the flow in the “Decision Zone”, and partially the “Discovery Zone”, such that adult and particularly juvenile surface-oriented anadromous fish, such as salmonids and alosines, are actively guided to a downstream surface bypass or collection system.
A guide wall (Fig. 1.1) is typically constructed of a series of floating partial-depth, impermeable panels. Depending upon the hydroelectric project configuration, the guide wall is anchored across a river channel, reservoir, or power canal (Scott, 2012). Scott (2012) explains that the concept is based on knowledge that: 1) juvenile anadromous fish tend to swim in the top portion of the water column (Whitney et al., 1997; Buckley and Kynard, 1985; Faber et al., 2011), 2) some juvenile species have been shown to select a shallow rather than deep passage route when given the choice (Johnson et al., 1997), and 3) anadromous juveniles tend to migrate downstream in the river thalweg (Whitney et al., 1997). It is thought that the floating guide wall designs originated after hydropower owners noticed fish accumulating along debris booms within a power canal, similar to the booms used for a floating guide wall.

Two early implementations of a guide wall were at the Bellows Falls Dam and the Vernon Dam on the Connecticut River in Vermont and New Hampshire, U.S.A. (TransCanada Hydro Northeast Inc., 2012; RMC Environmental Services, 1991). Each of these two guide walls were constructed as fixed concrete structures. At the Bellows Falls Dam a high number of Atlantic salmon smolts passing through the turbine intakes
instead of the bypass between 1991 and 1994 triggered the construction of the 200 ft.
long, 15 ft. deep (at normal impoundment elevation) guide wall set at a 45 degree angle
to the flow in 1995. A radio telemetry study in that year’s migration season proved that
the device was highly effective by actively guiding 94% of the smolts to the bypass
(Hanson, 1999; TransCanada Hydro Northeast Inc., 2012). The next dam downstream on
the Connecticut River is the Vernon Dam. At this facility there is a 10 ft. high guide wall
in the forebay leading to a bypass sluice which passes approximately 3.7% of the
maximum station flow. The bypass efficiency for smolts was estimated to be 80% (RMC
Environmental Services, 1991).

An alternative to the fixed concrete guide wall used at both Bellows Falls Dam
and the Vernon Dam on the Connecticut River is the floating guide wall. These types of
guide walls have been installed in various locations starting at the latest in 1998 with the
primary intention of guiding either Pacific or Atlantic salmonids. Examples include at
the Lower Granite Dam on the Snake River in Washington, U.S.A. (Adams et al., 2001),
Lockwood Hydroelectric Project on the Kennebec River in Maine, U.S.A. (NextEra
Energy Maine Operating Services, LLC, 2010), Cowlitz Falls Dam on the Cowlitz River
in Washington, U.S.A. (Tacoma Public Utilities, 2010), and the Bonneville Dam located
on the Columbia River at the border of Oregon and Washington, U.S.A. (Faber et al.,
2011).

Adams et al. (2001) explains that the floating guide wall at the Lower Granite
Dam is a steel wall 1100 ft. long and 55-79 ft. deep angled towards a surface bypass
collector immediately upstream of the turbine intakes. Biotelemetry and hydro-acoustic
studies showed that mean residence times in the forebay for chinook salmon, hatchery
steelhead, and wild steelhead collected when the guide wall was present increased by 1.6, 1.7, and 2.4 times than when the guide wall was removed. In addition, turbine entrainment was decreased by 16% when the guide wall was present causing the authors to believe this is a viable option to improve downstream passage of anadromous fish (Dauble et al., 1999; Scott, 2012).

The guide wall in the Lockwood power canal was 4 ft. deep and 300 ft. long (NextEra Energy Maine Operating Services, LLC, 2010) and made of an impervious rubber material. Attached to the bottom of the guide wall was 6 ft. of 7/16 in. Dyneema® netting. While NextEra Energy was testing the floating guide wall for its resistance to tearing, debris loading, and other structural issues, they observed juvenile clupeids being guided to the fish bypass at the terminus of the wall. However, they also observed juveniles on the downstream side of the wall that either sounded under the wall or passed through tears in the structure. Later, in 2010, the floating guide wall was replaced due to structural issues by a new guidance device. The new device is a 10 ft. deep permeable structure made of perforated plates and netting (Brookfield White Pine Hydro LLC, 2014). These types of permeable structures are common because they reduce the hydrodynamic force being applied on the structure by allowing some water to pass through and can be more buoyant. However, the sweeping velocity along the guidance device is reduced and the normal velocity perpendicular to the device is increased which can cause impingement and/or entrainment.

The guide wall at Cowlitz Falls Dam in 2010 was composed of a 4 ft. deep screen panel and attached below that was a 15 ft. tarp panel (Tacoma Public Utilities, 2010). The goal of this guide wall was to guide fish to a surface collector in order to trap and
transport out-migrating fish to downstream of the dam. An acoustic telemetry study that evaluated juvenile steelhead, Coho salmon, and Chinook salmon showed that the guide wall influenced the behavior of outmigrants and that more fish than expected arrived at the terminus of the wall (76 to 93% by species). The study also identified the following possible areas for future evaluation: positioning the collector entrance at the wall terminus, increasing attraction flow into the collector, extending the depth of the guide wall, and increasing its rigidity to maintain a vertical orientation (Tacoma Public Utilities, 2010). The following year the United States Geological Survey performed a radiotelemetry evaluation again studying juvenile salmonids (Kock et al., 2012). The guide wall evaluated in the previous year was replaced by a 10 ft. deep, steel panel floating guide wall. 40 to 63% of the fish by species arrived at the fish collection discovery area and movement patterns showed that the floating guide wall was effective at guiding fish along the device. However, the movement patterns also showed that the fish had a strong tendency to sound under the wall and on to the turbine intakes where 33 to 52% of the fish by species passed downstream (the largest percentage of all the passage routes).

The guide wall installed at the Bonneville Dam is 700 ft. long and 10 ft. deep (Faber et al., 2011). The US Army Corps of Engineers evaluated the guide wall’s impact on the passage and survival of juvenile salmonids (yearling Chinook salmon, subyearling Chinook salmon, and juvenile steelhead) by an acoustic-telemetry study at the site. The study showed that the guide wall improved collection efficiency for the yearling Chinook salmon but no discernable difference was noted for the other two fish species when compared to the prior year’s testing when no guide wall was present. Important to note
from this study is that between 45 and 50% of the fish that passed through the turbines went under the wall to get there. The other 50% went through gaps on the north and south side of the structure. This indicates that the design could likely be altered to reduce the number of fish passing below and around the structure.

Ongoing in 2014, the California Department of Water Resources (CA DWR) is studying a 5 ft. deep floating guide wall for use in the Sacramento River located in California, U.S.A. The purpose of the guide wall is to prevent out-migrating juvenile salmonids in the Sacramento River from being entrained into the Georgiana Slough. Lab-scale physical modeling was performed and the researchers found that the guide wall panels oriented at 22 degrees to the flow resulted in neutrally buoyant beads guiding along and not passing under the guide wall (personal communication, Shane Scott, 3/14/14).

Several other studies have been performed using computational fluid dynamics (CFD) as a means to better understand how a guide wall will impact the flow field in a forebay. The U.S. Army Corps of Engineers studied the impact of a guide wall in the forebay of the Dalles Dam located on the Columbia River which borders Oregon and Washington, U.S.A. (Rakowski et al., 2006). The report analyzed a 40 ft. deep guide wall set at 30 degrees and another at 45 degrees from the face of the powerhouse, each starting in the same upstream location. If juvenile out-migrating fish follow the flow path alone, then in most scenarios it was shown that the guide wall will not be successful in guiding fish. The study showed that the flow path goes briefly along the guide wall and then passes under and enters into a helical recirculation pattern along the backside. Interestingly, at the Bonneville Dam guide wall fish have been entrained in this
recirculation and guided to the bypass (Scott, 2012). The extent of helical recirculation is influenced by the depth and angle of the structure (Rakowski et al., 2006).

Another CFD approach to studying a guide wall was performed by Lundstom et al. (2010). The authors examined guide walls in the Pite River in Sweden upstream of a spillway and turbine intakes at a hydroelectric facility. The goal of the guide walls were to direct the surface oriented juvenile smolts towards the spillway instead of the turbine intakes. The authors studied ten guide wall configurations with different lengths (260 to 470 ft.), curvatures (straight, bend in downstream end, full bend with small radius, full bend with large radius, etc.), and depths (5.6 to 8.2 ft.). The study found that the guide wall performed best at low spilling rates and the device should stretch over a major part of the width of the river. An important metric used in this analysis was the acceleration along the guide wall and the acceleration downward upstream of the guide wall. The authors argued that a high acceleration downward upstream of the guide wall would improve guidance efficiencies because several other papers have shown that juveniles tend to avoid regions of high acceleration, as previously discussed. The authors were satisfied with the performance of the guide wall because the acceleration along the device was much smaller than that going downward, meaning the fish would choose the route along the device. While this may be true in certain cases, we argue caution because a downward acceleration that is too high may entrain the weak swimming juvenile fish and force them under the wall towards the turbines, as shown in NextEra Energy Maine Operating Services, LLC (2010), Kock et al. (2012), and Faber et al. (2011). An additional finding from Lundstrom et al. (2010) suggests the vertical velocity (z) component was affected at depths greater than twice that of the guide wall, but the
horizontal (x and y) components were mostly unaffected by the guide wall at depths below it.

There is a pressing need for technological innovations in the hydropower industry that can protect threatened aquatic species while maintaining efficient levels of hydropower production. A guide wall can help achieve these objectives, however, more research is needed to understand how the key design parameters affect the flow field and improve or deter fish passage. Novel to this study is the examination of the flow field upstream of a guide wall set at a wide range of depths and angles to flow and subject to a wide range of average approach velocities, all within an idealized power canal. New metrics, useful in the evaluation of guide walls, are presented. These metrics aim to explore the range of velocities and the strength of the downward flow signal a fish may encounter while swimming along a guide wall. The goal is to determine the combination of design parameters that will most likely increase the chance of surface-oriented fish being successfully guided to the bypass.

1.4 Methodology

1.4.1 Model Domain

To evaluate the flow field immediately upstream of a guide wall, a parameterized CFD model of an idealized power canal was constructed in © ANSYS Fluent v 14.5 (ANSYS Inc., 2012). Fluent is a finite-volume code that iteratively solves the conservation of mass and momentum over a set of discretized control volumes within the model domain until convergence. Fig. 1.2 displays the plan view of the power canal and a cross sectional view from the furthest downstream location at the bypass entrance. The
section downstream of the guide wall was not modeled to simplify the analysis. To accurately model head losses that are incurred by the structure a more complex model than is presented here is required.

For each scenario, the inlet location is fixed and the approach distance $\ell$ was held constant at 25 ft. The longitudinal length of the guide wall, $L$, varies according to the angle of the guidance structure, $\theta$. The canal width, $W$, was 100 ft. and the canal depth, $H$, was 40 ft. The width of the bypass was $0.1W$ or 10 ft. The depth of the bypass opening was $0.25H$ or 10 ft. The total flow through the model inlet, $Q_T$, the flow through the bypass outlet, $Q_B$, and the flow through the main power canal outlet, $Q_C$, vary

**Figure 1.2**: The schematic on the left shows the plan view of the idealized power canal. The hatched area (upstream of the guide wall and bypass entrance) is the modeled region. The schematic on the right shows the cross-sectional view from A-A, the furthest downstream location as seen on the plan view. The grey area is the guide wall. The black area is the wall directly below the bypass entrance. Note the x-y-z axis, the intersection of the x and y axis always occurs at the most upstream section of the guide wall, as shown above. On the x-axis, the bypass outlet is located at $x = L$ and the model inlet is located at $x = -\ell$. For each scenario, the inlet location is fixed and the approach distance $\ell$ was held constant at 25 ft. The longitudinal length of the guide wall, $L$, varies according to the angle of the guidance structure, $\theta$. The canal width, $W$, was 100 ft. and the canal depth, $H$, was 40 ft. The width of the bypass was $0.1W$ or 10 ft. The depth of the bypass opening was $0.25H$ or 10 ft. The total flow through the model inlet, $Q_T$, the flow through the bypass outlet, $Q_B$, and the flow through the main power canal outlet, $Q_C$, vary.
depending upon the average approach velocity, \( V \). The percent of the total flow through the bypass, \( p \) (equal to \( 100 \times Q_b/Q_t \)), for all model runs was 5%. The size of the bypass opening and the percent of the total flow through the bypass (\( p \)) are within the typical range for surface flow outlets (Johnson and Dauble, 2006) and \( p \) is also within the range of design criteria used by the US Fish and Wildlife Service in the Northeast (Odeh and Orvis, 1998).

### 1.4.2 Model Parameters

The key parameters relevant to this work are the depth of the guide wall, \( d \), the angle of the guide wall, \( \theta \), and the average inlet velocity, \( V \). There are a total of 40 scenarios. Table 1.1 displays the ranges and intervals each parameter is evaluated on:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of the Guide Wall (( d ), ft)</td>
<td>10 to 20</td>
<td>3.33</td>
</tr>
<tr>
<td>Angle of the Guide Wall (( \theta ), deg)</td>
<td>15 to 45</td>
<td>7.5</td>
</tr>
<tr>
<td>Average Inlet Velocity (( V ), ft/s)</td>
<td>2 to 4</td>
<td>2</td>
</tr>
</tbody>
</table>

The range of \( d \) was chosen because it represents a set of typical values found within the literature. Only one guide wall mentioned in the Background (Section 1.3) of this chapter had a depth less than 10 ft., and that guide wall is in a testing stage. While guide walls have been set deeper than 20 ft., the designs are less common and are for deeper a canal and forebay. The range of \( \theta \) is typical for surface guidance technologies and all guide walls referred to in the literature are within this range. The range of \( V \) is also typical within a power canal, although 2 ft/s is more common. A value for \( V \) of 4 ft/s is very high for a power canal.
1.4.3 Boundary Conditions

Three different types of boundary conditions (BC) are used in each of the model scenarios. The first type of BC is a velocity inlet. The inlet is defined using a velocity profile characteristic of a fully developed viscous flow with an average inlet velocity, V. The velocity profile for \( V = 2 \text{ ft/s} \) is shown in Fig. 1.3. To attain each developed flow profile, a rectangular channel CFD model was constructed, termed the Inlet Calculation CFD Model (ICCM). The ICCM used a cross section at the inlet of the Idealized CFD Model and extruded it long enough such that fully developed flow could be achieved. In each ICCM run, the inlet was set to a uniform velocity equal to V and the outlet was specified as an outflow carrying 100% of the flow. Identical solvers, described later, were used for both the ICCM runs and the Idealized CFD Model. The velocity profile at the outlet of the ICCM is used as the velocity profile at the inlet of the Idealized CFD Model. In addition to the velocity profile, the turbulence intensity (defined as the root-mean-square of the turbulent velocity fluctuations divided by the mean velocity) is

![Velocity Contour Plot](image)

Figure 1.3: The contour plot on the inlet of the CFD model geometry represents the velocity specified as a BC in the case of \( V = 2 \text{ ft/s} \). Note the fully developed flow profile. The arrow represents the direction of flow. The model domain is indicated by the black outline in this 3-D view.
specified at 5%. © ANSYS Fluent v 14.5 (ANSYS Inc., 2012) recommends the use of 5% in the event this value is unknown, as it is in this case.

The second type of BC is a pressure outlet. This outlet type is defined in two locations: 1) directly under the guide wall and 2) through an entrance to a bypass. The two white areas in the cross-section A-A for Fig. 1.2 depicts each of the BC locations. Each outlet is prescribed a hydrostatic pressure distribution and a target mass flow rate corresponding to the percentage of flow through the bypass, p. The streamlines are converging at the pressure outlet specified below the guide wall, because of this a hydrostatic pressure distribution is not entirely accurate. However, this will likely have a minimal impact on the results as the pressure distribution should only be slightly different from hydrostatic. In a physical test performed on a lab-scale model guide wall (from Chapter 2), the estimated pressure below the wall was essentially hydrostatic.

The third type of BC is a wall condition with a specified shear and roughness height value. The water surface is defined as a slip-condition with a specified shear stress of zero and zero roughness because shear stress at the water-air interface can be considered negligible. The channel walls and bottom are defined as a no-slip condition, with a defined roughness height of 1.64 x 10^{-2}. The face of the guide wall is also defined as a no-slip condition, but the roughness height is 8.20 x 10^{-2}. An actual guide wall exterior is often composed of a rubber or stainless steel.

1.4.4 Mesh

In all scenarios for both the Idealized CFD Model and the ICCM, the domains were divided into a number of finite volumes in the form of tetrahedrons. Face and body sizing rules were applied in different regions of the domain. The smallest cells occur
near the boundaries and guidance structure. The element face sizing on the guidance wall ranged between 0.8 and 1.6 ft. The face sizing on the pressure outlets ranged between 1.0 and 1.6 ft. Inflation layers were used to accurately model the wall roughness effects on the flow field. The inflations layers were applied at all boundaries of the model, including the guide wall. The aspect ratio, orthogonal quality, and skewness were the primary metrics used to evaluate mesh quality. Number of finite volumes ranged from approximately 350,000 to 512,000.

### 1.4.5 Solver and Convergence Criteria

All CFD runs performed in this analysis use the second order upwind method to solve the conservation of momentum equations for steady-state conditions. The runs are solved using the SIMPLE scheme (Patankar and Spalding, 1972) as the pressure-velocity coupling method. The realizable k-ε turbulence closure model with standard wall functions is used to describe the turbulent kinetic energy and turbulent dissipation rate. Similar to momentum, the turbulence model is solved using the second order upwind method. However, in all scenarios each model was first solved using the first order upwind scheme. The results of the first order upwind solving scheme were used as the initial solution to the second order upwind solver. This provided a means to reach convergence quicker. Convergence criteria included the equation residuals for continuity, x-velocity, y-velocity, z-velocity, turbulent kinetic energy, and turbulent dissipation rate. Additional monitors included the integral of the velocity magnitude on the outlet below the guide wall, integral of velocity magnitude on the outlet to the bypass, total volume integral of the velocity magnitude in all fluid cells, the integral of the skin friction coefficient on the guidance face, and the total volume integral of turbulent kinetic
energy in all fluid cells. Additional details regarding the conservation of momentum and turbulence solvers can be found in the © ANSYS Fluent v. 14.5 code documentation manual (ANSYS Inc., 2012).

1.5 Results

1.5.1 Velocity Magnitude, Components, and Distribution

Fig. 1.4 displays the velocity magnitude and components on three vertical planes in the y-z axis at different locations on the x-axis for the scenario where d = 10 ft, θ = 300, and V = 2 ft/s. The three planes are at x = 0.25L, 0.5L, and 0.75L, where x is equal to 0 at the model inlet. The model boundaries are shown in a sketched image around the contour plots. This figure shows several important points, all of which apply to each of

![Contour plots](image)

**Scenario: d = 10 ft, θ = 30°, V = 2 ft/s**

Figure 1.4: Contour plots of the velocity magnitude (far left), velocity in the x-direction (mid-left), velocity in the y-direction (mid-right), and velocity in the z-direction (far right) for the scenario of d = 10 ft, θ = 30°, and V = 2 ft/s. The top row plots are for a plane located at x = .75L. The middle row plots are for a plane located at x = .5L. The bottom row plots are for a plane located at x = .25L.
the 40 total scenarios. The maximum velocity magnitude occurs immediately below the guide wall, while directly beside the guide wall the water velocity magnitudes drop to levels below that of the average inlet velocity, \( V \). This drop in velocity correlates to an increase in the turbulence in the same region beside the guide wall. Second, the velocity component in the y-direction is shown to be negative in the upper portion of the water column and positive below the guide wall. This is expected as the guide wall is designed to create a strong sweeping velocity along the structure’s face toward the bypass. Third, the negative peak in the z-velocity component occurs directly at the bottom of the guide wall and the guide wall creates a high velocity gradient in the negative z-direction at the face of the wall. Fourth, the velocity distribution beside and below the guide wall is very similar at each of the locations.

**1.5.2 Maximum to Mean Velocity Ratio**

To compare the 40 scenarios, several metrics are formulated based on each scenario’s velocity output. The first metric introduced is the Maximum to Mean Velocity Ratio (MMR), calculated as the ratio of the maximum velocity magnitude along the guide wall to the average inlet velocity magnitude (\( V \)). The maximum velocity magnitude is determined on a specified plane within each model domain. The specified plane is vertical in the y-z axis, is at the longitudinal midpoint of the guide wall (where \( x = 0.5L \)), and extends from the water surface to the bottom of the guide wall. Fig. 1.5 shows the results in a contour plot for both \( V = 2 \) ft/s and \( V = 4 \) ft/s.

Interestingly, the average approach velocity has minimal impact on the MMR. The values under all configurations range from 1.14 to 1.62, with the lowest for a guide wall design of \( d = 10 \) ft and \( \theta = 15^0 \) and the greatest for a design where \( d = 20 \) ft and \( \theta = \)
Also, recalling from Fig. 1.4, the peak velocity magnitude occurs at the very bottom of the guide wall near the face of the wall. This is consistent throughout all 40 scenarios.

The DSR at each cell of the model is calculated using the following formula:

1.5.3 Downward to Sweeping Velocity Ratio

As noted in the Introduction (Section 1.2), a problematic feature of a guide wall is that it can create a strong downward flow component likely leading to a reduction in guidance efficiency. The next metric formulated is the Downward to Sweeping Velocity Ratio (DSR), or the ratio of the velocity in the z-direction to the magnitude of the x and y velocity components. Here the authors’ assume (based in part on the rheotactic behavior of fish) that the larger the absolute value of the Z-Velocity Ratio, the more likely a fish will be to volitionally follow the downward current or be entrained below the guide wall.
\[ DS\text{R} = \frac{V_z}{\sqrt{V_x^2 + V_y^2}} \]  
Eq. 1.1

Where \( V_z \) is the velocity in the z-direction, \( V_x \) is the velocity in the x-direction, and \( V_y \) is the velocity in the y-direction. The sweeping velocity (denominator of the DSR) at an elevation above the bottom of the guide wall is always in the direction of the bypass whereas the downward velocity (numerator of the DSR) points to below the guide wall. Fig. 1.6 displays a DSR contour plot on a vertical plane in the y-z axis at the longitudinal midpoint of the guide wall (\( x = 0.5L \)) for the scenario of \( d = 10 \text{ ft}, \theta = 30^\circ \), and \( V = 2 \text{ ft/s} \). A negative value indicates a downward flow, away from the water surface.

Figure 1.6: A contour plot of the DSR for the scenario of \( d = 10 \text{ ft}, \theta = 30^\circ \), and \( V = 2 \text{ ft/s} \) taken at the longitudinal midpoint of the guide wall (\( x = 0.5L \)) on a vertical plane in the y-z axis. The black rectangle in the top right indicates the location of the guide wall. Recall the WSE = 40 ft.
1.5.4 Minimum DSR

Fig. 1.6 shows a typical distribution of the DSR taken at a plane at any x-location along the guide wall. There is a distinct DSR gradient that occurs along the face of the guide wall in the z-direction where the values range from approximately 0 at the water surface to -0.825 at the bottom of the guide wall. This gradient exists for each scenario, consisting of a DSR of approximately 0 at the water surface and a minimum value occurring along the very bottom of the guide wall, although the minimum value changes depending upon the depth and angle of the structure. The location of the Minimum DSR is the same location where the velocity magnitude reaches its maximum value. Thus under this condition, a fish swimming along the bottom of the guide wall might be more likely to be entrained beneath it rather than safely guided to the bypass.

By finding the Minimum DSR for each scenario, the authors are able to state if the worst-case conditions along the guide wall are sweeping dominant (DSR > -1.0) or downward dominant (DSR < -1.0). Therefore, in the case that the Minimum DSR is greater than -1.0, it is known that conditions from the water surface elevation (WSE) to the bottom of the guide wall are sweeping dominant. However, if the Minimum DSR indicates that a specific scenario is downward dominant, then it is known that there is a transition point somewhere between the WSE and the bottom of the guide wall where the flow field shifts from sweeping dominant to downward dominant. This “transition depth” (later referred to as d*(t* = -1)) is investigated in the following sub-section (1.5.5).
Fig. 1.7 displays two contour plots (for V = 2 ft/s and V = 4 ft/s) which illustrate how the Minimum DSR changes depending upon the depth and angle of the structure. The values range from approximately -0.4 (d = 10 ft, θ = 15°) to -2.3 (d = 20 ft, θ = 45°).

1.5.5 Upper Guidance Zone Depth, d*

Given a DSR threshold value (t*), the guide wall can be split from the water surface elevation (WSE = H = 40 ft) to the guide wall depth, d, into two separate zones. For a given t*, the minimum depth (equivalent to the maximum elevation) at which the DSR is equal to or less than t* is the Upper Guidance Zone Depth (d*(t*)). For example, referring back to Fig. 1.6 and given a t* = -0.4, d*(t* = -0.4) ≈ 7.5 ft. The volume above the elevation at depth d*(t*) possesses a DSR greater than t* and the volume below
possesses a DSR less than or equal to $t^*$. The metric is based on the hypothesis that, due to a guide walls tendency to create strong downward flows along its face, the guide wall can be split into an “Upper Guidance Zone (UGZ)” and a “Lower Guidance Zone (LGZ)”. The UGZ is considered to be more likely to effectively guide fish because of its reduced absolute value of the DSR. The LGZ is considered to be less likely to effectively guide fish because of its greater absolute value of the DSR. Fig. 1.8 shows for $V=2$ ft/s and $V=4$ ft/s how the dependent variable $d^*(t^*)$ changes with the independent variable $t^*$. The minimum $d^*(t^*)$ is zero and the maximum is the depth of the guide wall, d.

The impact of changing the guide wall depth and angle on $d^*(t^*)$ is evident in Fig. 1.8. For instance, the value of $t^*$ where $d^*(t^*)$ equals guide wall depth, d, changes dramatically from -0.8145 for a guide wall design of $\theta = 15^\circ$ and $d = 20$ ft. to -2.2715 for a guide wall design of $\theta = 45^\circ$ and $d = 20$ ft. This is also evident when changing the guide wall depth as $d^*(t^*)$ first equals d ranging from -1.4965 to -2.2715 for guide wall

![Figure 1.8: Plots of $d^*(t^*)$ versus the DSR Threshold, $t^*$, for $V = 2$ ft/s (left) and $V = 4$ ft/s (right).](image-url)
designs where $\theta = 45^0$. Note that when $d = d^*(t^*)$ there is a DSR greater than $t^*$ along the full depth of the guide wall.

Also of note is that $d^*(t^*)$ is nearly identical for each average inlet velocity. This implies that when calculating the DSR a change in velocity within the power canal is much less important than the design parameters of the guide wall. However, the actual $z$-component of the velocity will obviously change in response to the prescribed average inlet velocity, $V$.

Fig. 1.9 better illustrates the difference between $d^*(t^*)$ and $d$ for all combinations of guide wall depths and angles with an Average Inlet Velocity, $V$, equal to 2 ft/s and $t^*$ equal to -1 (left), -0.67 (middle), and -0.33 (right). The transition depth alluded to in the previous sub-section (1.5.4) is represented in the left contour plot.

Most noticeable from Fig. 1.9 is that the difference between the guide wall depth, $d$, and the UGZ Depth, $d^*$, increases as $t^*$ is reduced. This is expected as the threshold becomes more restrictive. This also shows the advantages of a lesser angle, particularly

![Figure 1.9: Contour plots of the Upper Guidance Zone Depth, $d^*(t^*)$ for $t^* = -1.0$ (left), $t^* = -0.67$ (middle), and $t^* = -0.33$ (right). The guide wall depth, $d$, is on the x-axis and the guide wall angle, $\theta$, is on the y-axis. The average inlet velocity, $V$, is equal to 2 ft/s. The black circles indicate the data point locations, corresponding to each combination of depth and angle run in the CFD analysis. The contour lines are the result of a linear interpolation between data points.](image-url)
for the $t^*$ values closer to zero. For example, the difference in $d^*(t^*=-.33)$ for the scenario of $\theta = 15^\circ$ and $d = 20$ ft. and the scenario of $\theta = 45^\circ$ and $d = 20$ ft. is approximately 10 ft. This difference is half of the guide wall depth for those scenarios. For these same two scenarios the difference in $d^*(t^*=-1)$ is approximately 6 ft.

1.6 Discussion

CFD is an approximation of real-world hydraulics and the authors acknowledge it’s limitations in predicting guidance efficiency. However, CFD is based in physical laws that give it the capability to produce accurate and reliable results. Consequently, the results of this analysis rely greatly on an accurate description of the boundary conditions, the discretized mesh, and the second order solvers. In addition, the model domain is an idealized power canal and is not representative of a real hydropower project, which may have much more complex hydraulics. Furthermore, the use of a single phase model results in a loss of model resolution near the water surface boundary layer, although this is not expected to make a substantial difference in the results and is a common simplification when wave action is not integral in the analysis.

Without testing fish movement and behavior in situ in response to guide walls, it is difficult to predict how a fish will respond to the flow conditions. Although generalized metrics partially based on the behavior known as rheotaxis were formulated, the results can in no way estimate actual fish behavior. Each of the metrics developed are based entirely on the velocity output data from the CFD analysis. Fish behavior is also impacted by hydraulic conditions such as acceleration and turbulence (Larinier, 1998), but fish also possess complex and unpredictable behaviors in response to environmental
conditions both inclusive and exclusive of hydraulics. Inclusion of some of these variables in the evaluation of each scenario could make for a more sound approach to understanding how fish will behave near the guide wall.

Other physical aspects of the structure have been ignored. The forces applied to a guide wall may create a vertical tilt such that the guidance wall is not perpendicular to the water surface. In addition, a curvature often develops when looking from plan view. Ideally, strengthening of the structure and anchoring it to the bottom could minimize the deflection. More research is needed to investigate the hydraulics of tilted/deflected guide walls.

Conversely, this research and the derived metrics offer ways to evaluate and compare each guide wall design relative to one another based on each’s upstream flow field. These results can also be used to make an educated guess as to how out-migrating anadromous fish will respond to the hydraulic conditions. Considering the information gleaned from this study, a relatively small angle (the minimum was $15^\circ$) is likely to produce conditions favorable to efficient guidance. Both the MMR and the Minimum DSR show that as the angle is increased 1) smaller juvenile fish should be more likely to be entrained below the guide wall and 2) larger adult fish should be more likely to volitionally pass below the guide wall.

Regarding the guide wall depth, a recommendation needs to be informed by site-specific data. This includes, but is not limited to, the target species/life stages and the vertical distribution of those out-migrating fish. Consequently, the authors recommend that the guide wall be set deep enough such that $d^*(t^* > -1)$ is greater than the maximum depth of the expected vertical distribution of all the target fish species at the site. The
assumption of $t^* > -1$ is applied to ensure sweeping dominant conditions and is designed to both take advantage of the negative rheotactic fish response and to guide any passively drifting juvenile fish. DSR threshold values closer to zero are likely to be more effective at reducing the number of fish that pass below the guide wall.

1.7 Conclusion

Guide walls have been utilized to improve downstream passage survival for anadromous fishes including salmonids and alosines over the past 20 plus years. Less frequently implemented than other surface guidance technologies (e.g. louvers, bar racks, screens, among others), they are gaining popularity, particularly in the northwestern United States. This body of research focuses on the basic design parameters and begins to answer the question of which configuration might enhance fish guidance. A CFD approach is used to answer this fundamental question. The key findings indicate that a guide wall set at a small angle and deep enough such that $d^*(t^* > -1)$ covers the expected vertical distribution of the approaching fish is more likely to produce hydraulics favorable for efficient guidance. Future work is necessary, particularly to investigate other guide walls configurations and perform more rigorous full-scale testing in situ with the various fish species of interest.
CHAPTER 2

A PHYSICAL MODELLING APPROACH TO EVALUATING THE FLOW FIELD UPSTREAM OF A PARTIAL-DEPTH GUIDE WALL FOR DOWNSTREAM FISH PASSAGE

2.1 Abstract

Impermeable guidance structures (or guide walls) are used to improve passage efficiency and reduce delay of out-migrating anadromous fish species. Their purpose is to guide the fish to a bypass (i.e. a sluice gate, weir, or pipe) allowing the fish to circumvent the turbine intakes and safely pass downstream. In this study, a set of nine experiments were conducted to measure the 3-dimensional velocity components upstream of a guide wall set at a wide range of guide wall depths and angles to flow. Results demonstrate the effect of the guide wall angle and depth on both the peak velocity magnitude and the ratio of the downward vertical velocities to sweeping velocities along the guide wall. The results corroborate the findings of Chapter 1 in which a computational fluid dynamics model was used to perform a similar analysis.

2.2 Introduction

Partial-depth guide walls are prescribed to improve downstream fish passage at hydroelectric facilities (Schilt, 2007). They are intended to actively guide fish to a safer passage route (i.e. the bypass) and protect fish from entering into turbine intakes. The target species for these structures include a wide range of surface oriented anadromous and potadromous fish.

Notably, monitoring studies have shown that there is a high propensity for the target fish species to pass underneath the guide wall rather than be guided to the bypass
These unguided fish may either be 1) exhibiting a negative rheotactic behavior, 2) becoming fatigued to the point of entrainment (after attempting to swim against the downward flow field), 3) physically unable to swim against the encountered velocities, or 4) responding to some other stimuli (e.g. turbulence, velocity gradients, acceleration, sound, light).

Chapter 1 investigated the key design parameters of a guide wall (angle to approach flow, depth, and average approach velocity) through the use of a computational fluid dynamics (CFD) model in ANSYS Fluent V. 14.5 (ANSYS Inc., 2012). The key findings illustrated the depth to which sweeping dominant conditions prevail under a wide range of guide wall depths and angles. Based on the rheotactic response of fish and the low swimming capabilities of juvenile fish, the authors recommended the use of a guide wall which produced sweeping dominant conditions within the expected depth of the approaching target fish species. In this paper, the authors compare the findings from a lab scale physical model with those of Chapter 1 and further detail the flow field immediately upstream of a guide wall.

2.3 Experimental Design

The experiments were performed in a rectangular open channel (3 feet wide, 4 feet deep, and 16.25 feet long, with a plywood floor and acrylic sides), hereafter referred to as the flume, at the USGS Conte Anadromous Fish Research Center located in Turners Falls, Massachusetts, USA. The flume was attached to head and tail tanks that introduced flow to and received flow from the flume (Fig. 2.1). The head tank received
the flow of water through a 10” pipe connected to a pump which raised the water from a sump below the laboratory room floor into the head tank. Flow into the flume was measured using differential pressure cells attached to a 12” venture meter located in the 10” pipeline immediately upstream of where the water entered into the head tank. The pipe line into the head tank was perpendicularly oriented to the head tank floor. At the base of the pipe, two 6” wide by 6” high slits regulated the water flow into the head tank. Each opening forced the water in the direction of the upstream head tank wall. A total of

Figure 2.1: A schematic of the laboratory, showing all water diversions.
3 screens placed perpendicular to the head tank floor were used to diffuse the flow into the flume, removing a significant portion of the entrained air and creating a more uniform velocity distribution at the entrance. There were two outlets in the tail tank, the majority of flow went through a regulating sluice gate which allowed adjustments to the water surface elevation in the flume. The remainder of the flow was directed through a low flow outlet which was a 2” diameter circular opening on the tail tank floor.

Within the flume, a guide wall was constructed of a series of ¾” double-sided MDO plywood panels. The guide wall was fixed in place on the upstream end to a wooden piece attached to the flume wall via a clamp and on the downstream end to the bypass reservoir via a hinge fixed onto the bypass reservoir wall. The hinge allowed the modelers to change the angle of the guide wall. This design led to minor differences in the velocity distribution at the start of the guidance wall (discussed further in the Experimental Results Section 2.4) due to slight but unavoidable variations in guide wall geometry. The hinge was attached such that it could be shifted up and down to change the depth of the guide wall. The bypass reservoir was constructed of ¾” double-sided MDO plywood and the existing plywood floor and acrylic sides of the flume. The reservoir was 3” wide, 30” high, and 34.5” long. Water flowed into the bypass reservoir over a sharp-crested rectangular weir made of aluminum. The weir was set in place such that it could be shifted up and down to change the amount of flow into the weir. Water exited the bypass reservoir via a 3” diameter circular outlet near the base of the reservoir. A 5 hp pump was used to extract the water from the reservoir. A valve placed at the outlet of the pump regulated the flow out of the bypass reservoir. Flow measurements into the bypass reservoir were made using the rectangular weir equation (Crowe et al.,
The coefficient of discharge was estimated using the Rehbock Equation (Rehbock, 1929), which takes into account the depth of the water upstream of the weir and the height of the weir. The water elevation within the bypass reservoir was also measured to ensure a steady-state condition within the reservoir.

The laboratory model is a scaled down version (1:20) of an idealized guide wall configuration set in a rectangular power channel, referred to as the prototype. Fig. 1.2 shows the laboratory model schematic (same as the CFD model). Note the x-y-z axis orientation for later reference. Emphasis is placed on the laboratory model to display similarity in form (geometric similarity), motion (kinematic similarity), and forces (dynamic similarity) to the prototype, as recommended by Chanson (1999). The primary force ratios considered are the Froude number (a ratio of the inertial force to the gravitational force) and the Reynolds number (a ratio of the inertial force to the viscous force). The laboratory model and the prototype possess identical Froude numbers, although they vary significantly in Reynolds number. Acknowledging this limitation, the goal becomes to ensure that turbulent flow (Re > 10^4) exists in all laboratory model versions. It is important to note that 1) it is impossible to match both Froude and Reynolds numbers for a prototype and laboratory model, 2) Froude similarity provides the best results for models where friction effects are negligible, and 3) significantly greater velocities in the laboratory model are required to match the prototype Reynolds number making it infeasible to perform in the laboratory setting of this study (Heller, 2011). Table 2.1 details each laboratory model configuration and the associated prototype model. Other pertinent parameter values that are fixed include W (channel width: 30 in. -- laboratory, 50 ft. -- prototype), H (water depth: 30 in., 50 ft.), w
(rectangular weir width: 3 in., 5 ft.), b (head of water above rectangular weir: 3.6 in., 6 ft.), $Q_T$ (total flow rate into flume: 2.8 cfs, 5000 cfs), $Q_B$ (total flow rate into the bypass reservoir: 0.14 cfs, 250 cfs), and $Q_C$ (total flow rate under guide wall: 2.66 cfs, 4750 cfs).

The Reynolds number for each experiment at the start of the guide wall is approximately $2.65 \times 10^4$, for the prototype the value is approximately $2.37 \times 10^6$. The flow for both the prototype and laboratory experiments is subcritical ($Fr = 4.98 \times 10^{-2}$).

Table 2.1: Parameter values of each experiment, comparing the laboratory version to the prototype. $V$ is the calculated average approach velocity given the flow rate of the experiment and the water depth. The $L$ subscript refers to the laboratory version and the $P$ subscript refers to the prototype. All other parameters in the table were previously defined.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>$\theta$</th>
<th>$QB/Q_T$</th>
<th>Laboratory Version</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$V_L$ (fps)</td>
<td>$d_L$ (in.)</td>
<td>$V_P$ (fps)</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>0.05</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>0.05</td>
<td>0.4</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.05</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>0.05</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>0.05</td>
<td>0.4</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0.05</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
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<td>0.05</td>
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<td>6</td>
</tr>
<tr>
<td>8</td>
<td>45</td>
<td>0.05</td>
<td>0.4</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>0.05</td>
<td>0.4</td>
<td>10</td>
</tr>
</tbody>
</table>

To quantitatively evaluate the flow field, a SonTek Acoustic Doppler Velocimeter (ADV) was used to measure the velocity components in 3 dimensions. A grid was set up in the region upstream of the guide wall (see the hatched area of Fig. 1.2) and contour plots of the flow field were constructed using these data assuming a linear change between points. The grid was unevenly spaced, with tighter spacing closer to the guide wall and the water surface. Number of data points for each experiment ranged from 101 to 183, largely reflective of the change in space as the guide wall angle changed. Higher point densities at a cross-section were tested but were proven to be unnecessary to capture the velocity distribution occurring along the guide wall. Data were taken at
cross-sections at multiple locations along the guide wall, including immediately upstream of the start of the guide wall and immediately upstream of the bypass rectangular weir. In total 6 cross-sections were taken for Experiments 1-3, 5 for Experiments 4-6, and 4 for Experiments 7-9. For the purposes of this paper, the cross-section immediately upstream of the bypass weir was excluded. The flow field in this region is highly dependent upon the design/size of the bypass and thus is outside the paper’s scope. The probe collected data at a duration of 60 seconds per data point, which at a sampling rate of 25 Hz amounts to 1500 measurements per data point. Other time durations were tested (30s, 90s, 120s), but it was determined that 60s was adequate to obtain accurate and reliable velocity measurements. All reported velocity data in this study is the mean taken over the 1500 samples per data point.

2.4 Experimental Results

As illustrated in Chapter 1, the strong downward velocity component that exists along guide walls can negatively affect the guidance efficiency of these structures. The authors also proposed the idea of an Upper Guidance Zone (UGZ) depth for these structures, recognizing the fact that a lower section of the guide wall is less likely to guide fish to the bypass as a result of the higher downward velocity component in this region. Fig. 2.2 is a photo taken of the midway section of the guide wall for Experiment 6, where red dye was released directly onto the guide wall at multiple depths in the water column. The dye path lines clearly shows the varying degree in the downward velocity component from each of these locations, becoming greater the deeper into the water.
column. The blurring of the dye along the path lines is the result of dispersion (caused by turbulent conditions) and mechanical diffusion.

Considering this important and problematic feature of a guide wall, metrics are developed which seek to 1) determine the strength of the downward flow signal through use of the Downward to Sweeping Velocity Ratio (DSR) and 2) determine the peak velocity a fish may encounter through use of the Maximum to Mean Velocity Ratio (MMR). These two metrics, first introduced in Chapter 1, can be used to infer the possibility of a fish volitionally following or being entrained by the velocity field and forced underneath the guide wall (whether by fatigue or not having the physical capability of swimming fast enough to oppose the flow).

As a consequence of the method used to build the guide wall, the starting point varies for the experiments of different angles. This resulted in differing velocity distributions at x = L (the upstream starting point of the guide wall – see Fig. 1.2 for a

Figure 2.2: A photo taken of red dye released onto the guide wall of Experiment 6 at different depths. The water surface is directly above the top dye path line and the full depth of the guide wall is shown.
reference to the x-y-z axis). Fig. 2.3 shows a linearly interpolated contour plot of the mean of the velocity magnitude measurements (mean taken over the 1500 samples per data point) collected at $x = L$. The flow regime of each experiment shows some similarities, with the highest velocities occurring in the center of the flume, and the lowest along the walls. However, the maximum velocity magnitude and the velocity magnitude distribution differs as the starting point of the guide wall is shifted downstream with a change in angle.

![Figure 2.3: Contour plots of the mean velocity (mean taken over the 1500 samples per data point) for each experiment. Each row represents a different guide wall angle (15°, 30°, and 45° from top to bottom) and each column represents a different guide wall prototype depth (10 ft., 13.33 ft., 16.67 ft. from left to right). The black x-marks indicate the location of the data point. The black rectangle indicates the location of the guide wall. The contour plots are for the location of $x = L$]
The differences in velocity at the start of the guide wall impacts the velocity magnitude throughout the model domain. Table 2.2 displays the cross-sectional mean of the velocity magnitude above the bottom of the guide wall for each experiment. The mean is calculated from the linearly interpolated values between all the data points (with no extrapolation). The velocity magnitude mean in the region above the bottom of the guide wall at \( x = L \) varies from 0.42 fps to 0.5 fps for all the experiments, with the maximum occurring for Experiment 1 and the minimum for Experiment 9. For each experiment, the mean velocity magnitude changes only slightly at downstream cross-sections. The range of the mean velocity magnitude within each experiment is at most 0.04 fps, although all but Experiment 1 are less than or equal to 0.02 fps.

It should be noted that the average velocity at \( x = L \) varies only from 0.43 fps to 0.45 fps within the entire data collection area of the cross-sections (see the colored region of the cross-sections shown in Fig. 2.3). For the given flow rate, \( Q_r \), and the height of the water column, \( H \), it was expected to have an average velocity across the entire cross-section of the flume equal to 0.4 fps. The averages for each cross-section would shift closer to 0.4 fps if data for the entire cross-section of the flume were collected, as the lowest velocities occur along the flume bottom and side walls (due to frictional effects).

Unlike the mean velocity magnitude above the bottom of the guide wall, the maximum velocity magnitude (also shown in Table 2.2) is sensitive to both a change in the guide wall depth and the angle. Because of the differences in the mean velocity magnitude, this is best shown by the use of the Maximum to Mean Velocity Magnitude Ratio (MMR), calculated exactly as the name implies. For instance, at \( x = 0.38L \), Experiment 9 has a mean velocity magnitude above the bottom of the guide wall of 0.42
fps and a maximum of 0.62 fps, nearly a 50% difference (a MMR value of 1.46). At this same relative location Experiment 1 has a mean velocity magnitude of 0.5 fps and a maximum velocity of 0.54 fps, a difference of only 8% (a MMR value of 1.08).

Table 2.2: The table below displays four metrics (velocity magnitude mean, velocity magnitude maximum, MMR, and the minimum DSR) calculated at each cross-section of each experiment and only for the section of the cross-section above the bottom of the guide wall. The values are calculated from the linearly interpolated data points. Three sets of color-coded bars are used to help visualize the data.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Depth, (d_x) (ft)</th>
<th>Angle, (\theta) (deg)</th>
<th>Cross-section location, x-axis</th>
<th>Velocity Magnitude Mean (fps)</th>
<th>Velocity Magnitude Maximum (fps)</th>
<th>MMR</th>
<th>Minimum DSR</th>
</tr>
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<tbody>
<tr>
<td>1 10 15 L</td>
<td>0.50</td>
<td>0.57</td>
<td>1.14</td>
<td>-0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 10 15 L</td>
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<td>0.56</td>
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<td>-0.36</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1 10 15 L</td>
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<td>0.54</td>
<td>1.07</td>
<td>-0.32</td>
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<td></td>
<td></td>
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<tr>
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<td>0.54</td>
<td>1.08</td>
<td>-0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.52</td>
<td>1.09</td>
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<td></td>
<td></td>
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<td>1.17</td>
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<td>0.56</td>
<td>1.13</td>
<td>-0.43</td>
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<tr>
<td>2 13.33 15 L</td>
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<td>0.50</td>
<td>1.11</td>
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<tr>
<td>3 16.67 15 L</td>
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<td>1.11</td>
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<td>0.57</td>
<td>1.15</td>
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<td>0.57</td>
<td>1.15</td>
<td>-0.45</td>
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<tr>
<td>4 10 30 L</td>
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<td>0.52</td>
<td>1.12</td>
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<td>0.50</td>
<td>1.06</td>
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<td>0.53</td>
<td>1.11</td>
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<td>0.57</td>
<td>1.19</td>
<td>-0.49</td>
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<td>0.52</td>
<td>1.13</td>
<td>-0.38</td>
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<tr>
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<td>0.51</td>
<td>1.08</td>
<td>-0.31</td>
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<td>1.21</td>
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<td>0.57</td>
<td>1.22</td>
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<tr>
<td>6 16.67 30 L</td>
<td>0.46</td>
<td>0.51</td>
<td>1.12</td>
<td>-0.38</td>
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<td>1.30</td>
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<tr>
<td>7 10 45 L</td>
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<td>0.49</td>
<td>1.09</td>
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<td>7 10 45 L</td>
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<td>7 10 45 L</td>
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<td>7 10 45 L</td>
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<td>0.56</td>
<td>1.26</td>
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<td></td>
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<tr>
<td>8 13.33 45 L</td>
<td>0.43</td>
<td>0.49</td>
<td>1.14</td>
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<tr>
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<td>0.42</td>
<td>0.62</td>
<td>1.46</td>
<td>-1.01</td>
<td></td>
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</tr>
</tbody>
</table>
MMR above the bottom of the guide wall is shown in Table 2.2 for all cross-sections of each experiment.

Understanding how the guide wall depth and angle effect the peak velocity magnitude (and thus the MMR) is useful in the design of guide walls as higher velocities could pose a challenge to out-migrating fish. Table 2.2 shows that the MMR increases for both an increase in the depth and in the angle of the guide wall, with one variable’s influence not considerably outweighing the other. To demonstrate this, a two-factor ANOVA with replication was performed and a multiple linear regression was fit to the data set using the depth, angle, and cross-section location (measured by the actual x-location divided by L) as the independent variables and the MMR as the dependent variable. For the ANOVA test, only MMR values at cross-sections where $x = 0.79L$ and $0.28 L \leq x \leq 0.37L$ (total of 2 for each experiment) were used in the analysis. The authors chose these two cross-section regions because they are not too close to either the upstream or downstream end of the guide wall and to meet the requirement that each experiment must have the same number of values to complete the analysis. The ANOVA results show that a change in either the depth ($p = 8.87x10^{-4}$) or angle ($p = 3.97x10^{-6}$) of the guide wall will result in a significant difference in the MMR. For the multiple linear regression, a moderately low $R^2$ value was achieved (0.54) indicating the relationship is non-linear. The slope coefficients for each variable were calculated to be 0.0149 (p-value = 0.0012), 0.0043 (p-value = 8.6x10^{-5}), and -0.126 (p-value = 0.0061). This indicates that an increase in the depth or angle results in an increase in the MMR and that a decrease in the x-location results in a decrease in the MMR. It is interesting to note that an increase in the angle of 3.47° results in the same MMR increase as an increase in the
depth of 1’ (in prototype terms). However, the authors urge caution in generalizing this observation as the relationship is not fully explained by a linear regression and site-specific conditions would impact the regression equation.

A detailed look at the velocity components helps to understand the impact of the guide wall. Fig. 2.4 shows contour plots of the velocity magnitude and the velocity components (x, y, and z directions) for Experiment 9 (d_p = 16.67”, θ = 45°) at cross-section x = 0.79L. The black x-marks indicate the location of the data point. The black rectangles indicate the location of the guide wall.

Figure 2.4: Contour plots of the velocity magnitude (top-left), velocity x-direction (top-right), velocity y-direction (bottom-left), and velocity z-direction (bottom-right) for Experiment 9 at cross-section x = 0.79L. The black x-marks indicate the location of the data point. The black rectangles indicate the location of the guide wall.
section x = 0.79L. The velocity distributions shown here are a good representation of each cross-section taken at locations where x ≠ L. A pocket of slower moving water develops beside the guide wall in the top portion of the water column as the water around it accelerates downward acting as a partial barrier to movement, slowing the water down. Similar to Chapter 1, this pocket grows as the guide wall angle and guide wall depth are increased resulting in a large velocity gradient in the z-direction beside the guide wall. Here, again similar to Chapter 1, the maximum velocity magnitude across the entire cross-section occurs directly beside the very bottom of the guide wall. In the section of the cross-section above the bottom of the guide wall, the majority of flow is in the negative y-direction towards the bypass, and below the guide wall it is in the positive y-direction. Lastly, the peak of the velocity in the z-direction also occurs at the base of the guide wall, validating the Chapter 1 study.

The Downward to Sweeping Velocity Ratio (DSR) was calculated as the ratio of the velocity in the z-direction (the vertical velocity component) to the magnitude of the x and y velocity components (the sweeping velocity magnitude at locations along the face of the wall). Here the authors assume that the larger the absolute value of the DSR along the guide wall, the more likely fish will be entrained below the guide wall or (although untested) engage in a negative rheotactic behavior and swim below the wall. The DSR at each data point is calculated using the following formula:

$$ DSR = \frac{\bar{V}_z}{\sqrt{\bar{V}_x^2 + \bar{V}_y^2}} \quad \text{Eq. 2.1} $$
Where $\overline{V}_z$ is the mean velocity in the z-direction taken over the 60 second data collection period for each data point, $\overline{V}_x$ is the mean velocity in the x-direction, and $\overline{V}_y$ is the mean velocity in the y-direction. A negative value indicates a downward flow, away from the water surface.

Fig. 2.5 demonstrates the effect of a guide wall on the Z-Velocity Ratio for Experiment 9 (dp = 16.67’, θ = 45⁰) at cross-section x = 0.79L. The strong gradient in the z-direction of the DSR at the face of the guide wall is evident as values range from approximately -0.2 to nearly -1.4 directly beside the wall.
In general, negative DSR values exist throughout the data set, except for directly in front of the bypass weir. The magnitude of the metric increases both when the depth of the guide wall is increased and the angle is increased. The Minimum DSR occurs directly beside the very bottom of the guide wall, following a similar pattern to what is shown in Fig. 2.5. A 45 degree guide wall set at the deepest depth of 16.67’ (in prototype terms) results in the peak negative value of -1.35, whereas a 15 degree guide wall set at the shallowest depth of 10’ results in a Minimum DSR of only -0.3 (excluding the data at x = L). Table 2.2 lists the Minimum DSR over each cross-section and experiment and Fig. 2.6 displays the Minimum DSR recorded for each experiment but excluding the data at x = L.
An identical statistical analysis to that performed for the MMR was also completed for the Minimum DSR. The ANOVA results show that a change in either the depth ($p = 1.27 \times 10^{-3}$) or angle ($p = 1.35 \times 10^{-8}$) of the guide wall will result in a significant difference in the Minimum DSR. The multiple linear regression resulted in another moderately low $R^2$ value (0.67) indicating this relationship is also non-linear.

The slope coefficients for each variable (depth, angle, x-location) were calculated to be $-0.0291$ ($p = 0.0043$), $-0.0160$ ($p = 2.3 \times 10^{-8}$), and $-0.2585$ ($p = 0.0121$). This indicates that an increase in the depth or angle results in a decrease in the Minimum DSR and that an increase in the x-location results in an increase in the Minimum DSR. It is interesting to note that an increase in the angle of $1.82^\circ$ results in the same Minimum DSR decrease as an increase in the depth of 1’ (in prototype terms). However, the relationship is not fully explained by a linear regression.

Furthermore, a large gradient of the DSR in the z-direction forms directly beside the guide wall. For instance, Experiment 9 ($d_P = 16.67’$, $\theta = 45^\circ$) shows that a fish located near the mid-section of the guide wall at $x = .79L$ would experience a DSR of about -0.2 when swimming in the top 5 feet (in prototype terms) of the water column directly along the guide wall, but would experience a DSR of approximately -1.35 when traveling along the very bottom of the guide wall, between 15 and 20 feet deep. That change is dramatic and, along with the peak velocity magnitudes occurring at the bottom of the guide wall, supports the notion that these structures are ineffective at guiding fish to a bypass when traveling at a depth near the bottom of the guide wall.

To expand on this point, Table 2.3 shows a postulated Upper Guidance Zone (UGZ) Depth for each experiment. The UGZ Depth, introduced in Chapter 1, is
determined by finding the minimum depth (equivalent to the maximum elevation) at which the DSR is equal to or less than a DSR threshold, t*, shown in the table to vary between -0.1 and -1.4. The cells colored light blue indicate that the UGZ for the specified threshold is equal to the depth of the structure. The red colored cells indicate that the UGZ is equal to or less than the depth of the uppermost data point taken at each cross-section, a depth in prototype terms of roughly 4.2’.

Table 2.3: Postulated UGZ Depth (ft.) for each experiment in relation to a threshold DSR, t*.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Depth, (d_P) (ft)</th>
<th>Angle, (\theta) (deg.)</th>
<th>-0.1</th>
<th>-0.2</th>
<th>-0.3</th>
<th>-0.4</th>
<th>-0.5</th>
<th>-0.6</th>
<th>-0.7</th>
<th>-0.8</th>
<th>-0.9</th>
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<td>1</td>
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<td>≤ 4.2</td>
<td>6.2</td>
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<td>15</td>
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<td>4.5</td>
<td>9.4</td>
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<td>13.3</td>
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</tbody>
</table>

The postulated UGZ builds upon the work of Chapter 1. The authors developed the concept of the DSR and used it in the same manner to determine the UGZ. Instead of a laboratory model the authors used a computational fluid dynamics model (CFD) to run their analysis. To determine the UGZ based upon the results of a CFD model, the authors used a cross-section at \(x = 0.5L\) for all model scenarios. Here this analysis take a slightly different approach and characterizes the UGZ based on cross-sections located at \(0.79L\) where the absolute value of the Minimum DSR was greatest among the cross-sections collected. Table 2.3 shows that the postulated UGZ, given a relatively low threshold value of -0.4, increases for a decrease in the angle of the structure. However, it is unclear what the threshold truly should be, particularly when it is likely to vary by species and age of the fish. A greater knowledge of how fish respond to this particular metric and the
depth at which the fish approach the guide wall could lead to significant improvement regarding the application of the CFD and lab models.

2.5 Discussion & Conclusion

Over the past several decades, guide walls have been utilized to decrease entrainment and turbine mortality of anadromous out-migrating fishes. The experiments performed in this study focused on the hydraulic impact of the key design parameters (angle and depth) of these structures while building upon the work of Chapter 1. The key findings support with the conclusions made in Chapter 1, although there are some differences.

In the case of Experiment 9 (dP = 16.67', θ = 45⁰) where the angle is 45 degrees and the depth is 16 2/3’, the maximum velocity magnitude is roughly 50% larger than the average approach velocity. This result conflicts with that of Chapter 1, which reported a difference of 65-70%. Although, differences in the MMR between the results of this study and those Chapter 1 is not unexpected. The cross-sections are taken at a different location along the guide wall, but also the cross-section in the laboratory model does not account for the slowest velocities along the boundaries of the flume and near the water surface. This would lower the mean velocity magnitude and have no effect on the maximum velocity magnitude, implying an underestimation of the MMR.

This study also reported a Minimum DSR that tends to be slightly less than what was reported in Chapter 1. This can be partially explained by the ability of the CFD model to measure velocities much closer to the guide wall than what is capable within the flume. The ADV probe could only be positioned within 1 inch of the model guide wall,
translating to approximately 1.67’ in prototype terms. Measuring within this area would have permitted measurements of lower Minimum DSR values.

In addition, differences reported in the MMR and the Minimum DSR between this analysis and that of Chapter 1 can be explained through several other sources. Scale effects are present in the laboratory model, although this is believed to only contribute a small amount of error. The channel width is greater in the CFD analysis than in the laboratory analysis, contributing partially to the error. Perhaps most important, the velocity distributions are different between the laboratory and CFD models. The CFD models used a fully developed velocity distribution at the model inlet, but this was not attainable in the laboratory model, although efforts were made to produce as close to a fully developed velocity distribution as was possible. These sources of error, along the previously mentioned sources, all contribute to the differences reported in each of the studies.

Both the maximum velocity magnitude and the Minimum DSR occur at the bottom of the guide wall. The combination of these two peaks support the notion that, as Chapter 1 proposed, the bottom section of the guide wall is potentially ineffective at guiding fish to the bypass. Fish can either become exhausted swimming against these velocities or actively swim below the guide wall in an attempt to follow the flow field. Smaller juvenile fish will be at even greater risk of being entrained below the guide wall.

In consideration of these arguments, the author’s recommend that a guide wall be set deep enough such that the deepest point of the expected vertical distribution of the fish will be less than or equal to the UGZ Depth, given a threshold (t*) greater than or equal to -1.0. This design approach is thought to take advantage of the negative
rheotactic behavior of out-migrating fish by creating hydraulic conditions which provide a greater sweeping velocity than a downward velocity magnitude. However, a better understanding of fish distribution and behavior in the presence of these structures is required to know the true threshold of the DSR in which we use to measure the UGZ Depth.

The most effective method to increase the ratio of the UGZ Depth to the guide wall depth is by decreasing the guide wall angle. Therefore a 15 degree structure should outperform a 30 or 45 degree structure of the same depth given the same vertical distribution of the approaching fish. Increasing the guide wall depth will increase the UGZ Depth but it also results in higher peak velocities and a greater absolute value of the DSR in the ineffective region of the guide wall. Thus those fish traveling deeper than expected in the water column may have a lesser chance at being safely guided to the bypass. Therefore, it is likely a better practice to reduce the angle of the structure when possible rather than increasing the depth (unless of course the majority of the approaching fish are deeper than the guide wall).

Future work is necessary to refine guide wall design and operation, including 1) measuring the flow field under different approach velocities and different percent of flow to the bypass, 2) estimation of head loss and overall cost of the project, and 3) testing in situ with the various fish species of interest to better understand their behavioral response to the structure.
CHAPTER 3

THE HYDRAULIC IMPACT OF THE BYPASS FLOW PERCENTAGE UPSTREAM OF A PARTIAL-DEPTH GUIDE WALL FOR DOWNSTREAM FISH PASSAGE

3.1 Abstract

Partial-depth impermeable guidance structures (or guide walls) are used as a method to assist in the downstream passage of fish at a hydroelectric facility. However, guide walls can result in a strong downward flow causing the approaching fish to pass below the wall and into the direction of the turbine intakes. Chapter 1 and Chapter 2 showed that the ratio of the downward velocity to the sweeping velocity magnitude (DSR) is effected by a change in depth and angle of the guide wall. The objective of this study is to describe how the DSR changes along the full length and depth of a guide wall under a wide range of bypass flow percentages within a power canal. This paper focuses on two guide wall configurations, each set at an angle of 45 degrees to the approaching flow field and at a depth of 10 and 20 ft. The hydraulic conditions upstream of each guide wall configuration is shown to be impacted by a change in the bypass flow percentage, not only near the bypass but also at upstream sections of the guide wall.

3.2 Introduction

Partial-depth impermeable guidance structures (or guide walls) are used to actively guide out-migrating and surface-oriented diadromous and potadromous fish to a safe passage route around a hydroelectric facility. Guide walls typically consist of steel panels attached to a floating boom (Scott, 2012), although earlier designs used fixed concrete walls (TransCanada Hydro Northeast Inc., 2012; RMC Environmental Services,
The structures start at a location upstream of the hydroelectric facility in either a power canal or river channel and are angled toward the safe passage route (i.e. the bypass). The effectiveness of the guide wall varies by site, although many have been shown to be highly effective at guiding fish to the bypass (Scott, 2012). However, depending upon the depth and angle of the guide wall, these structures can create a high downward velocity (defined as the z-velocity component – see Fig. 1.2) and a low sweeping velocity (defined as the magnitude of the x and y velocity components – see Fig. 1.2) upstream of the wall. This can lead to fish passing below the wall by either volitionally following the flow or being entrained by it.

Chapter 1 and Chapter 2 studied the flow field upstream of a guide wall set at multiple depths and angles under different approach velocities. The authors developed a design methodology to ensure that fish approaching the wall given an expected vertical distribution will encounter sweeping dominant conditions (i.e. a greater sweeping velocity than downward velocity). The authors used both computational fluid dynamics (CFD) and a physical modelling approach. It was shown that a guide wall set at an angle in the range of 15 to 22.5° will result in a sweeping velocity magnitude equal to or greater than the absolute value of the downward velocity along the full depth of the wall and at each guide wall depth in the study (ranging from 10 to 20 ft.).

However, the Chapter 1 study focused on only the hydraulic conditions at the longitudinal midpoint of the guide wall and for a bypass flow rate equivalent to 5% of the flow rate in the power canal. Similarly, Chapter 2 analyzed the hydraulic conditions upstream of the guide wall for a bypass flow percentage of only 5%. Conversely, the Chapter 2 study did include an analysis of the hydraulic conditions at multiple cross-
sections along the longitudinal length of the wall. The objective of this paper is to examine the sensitivity of the primary metric used in Chapter 1 and Chapter 2, the Upper Guidance Zone Depth ($d^*(t^*)$), to changes in the bypass flow rate percentage ($p$) and to evaluate how this metric varies along the full length of the guide wall. The Upper Guidance Zone Depth is based on the hypothesis that, due to a guide walls tendency to create strong downward flows along its face, the guide wall can be split into an “Upper Guidance Zone (UGZ)” and a “Lower Guidance Zone (LGZ)”. The UGZ is considered to be more likely to effectively guide fish because of its smaller (in absolute value terms) downward to sweeping velocity magnitude ratio. The LGZ is considered to be less likely to effectively guide fish because of its greater downward to sweeping flow ratio. The ratio of downward velocity to sweeping velocity magnitude was previously defined by Chapter 1 as the DSR.

The UGZ Depth, $d^*(t^*)$, is defined as the depth at the maximum elevation where the DSR is less than a threshold value of $t^*$ along the guide wall. DSR values range from 0 to -2.3 in Chapter 1 and Chapter 2. A DSR value of approximately 0 indicates no downward flow and is typical near the water surface elevation. A DSR value of -2.5 indicates a downward velocity 2.3 times greater than the sweeping velocity along the face of the guide wall. Minimum DSR values were consistently located at the bottom of the guide wall.

3.3 Experimental Design

The CFD model of a full-scale guide wall and power canal developed in Chapter 1 was used to perform the evaluation. The model was constructed in © ANSYS Fluent v
Fluent is a finite-volume code that iteratively solves the conservation of mass and momentum over a set of discretized control volumes within the model domain until convergence. The CFD model was run in steady-state, used a second order solver for both momentum and turbulence, and consisted of approximately 350,000 finite volumes. Three different types of boundary conditions (velocity inlet, pressure outlets, and a wall condition) were used in each of the model scenarios. The realizable k-ε turbulence closure model with standard wall functions was used to describe the turbulent kinetic energy and turbulent dissipation rate. Convergence criteria included the equation residuals for continuity, x-velocity, y-velocity, z-velocity, turbulent kinetic energy, and turbulent dissipation rate. The generic model schematic is shown in Fig. 1.2.

For each scenario, the inlet location is fixed and the approach distance ℓ was held constant at 25 ft. The guide wall angle (θ) was 45° for all model runs and thus L, the total length of the model, was 115 ft. The canal width, W, was 100 ft. and the canal depth, H, was 40 ft. The width of the bypass was 0.1W or 10 ft. The depth of the bypass opening was 0.25H or 10 ft. The size of the bypass opening is within the typical range for surface flow outlets (Johnson and Dauble, 2006). The total flow through the model inlet, QT, was equal to 8,000 cfs and constant for all model runs. The flow through the bypass outlet, QB, and the flow through the main power canal outlet, QC, vary depending upon the bypass flow percentage, p (equal to 100*QB/QT). Eight different bypass flow percentage, p, values were used from 1% to 15% at an interval of 2%. Each bypass flow percentage was ran with a guide wall depth, d, of 10 ft. and 20 ft. The total number of model runs is 16.
Generally, a bypass flow percent ranges from 1 to 17% of the mean annual discharge, depending upon the type of bypass (Johnson and Dauble, 2006). The Northeast Region U.S. Fish and Wildlife Service typically prescribes a bypass flow percent of up to 5% of the power station hydraulic capacity (Odeh and Orvis, 1998), which is likely to be within the range described by Johnson and Dauble (2006). The other varied design parameter, \( d \), was set at the minimum and maximum value of the Chapter 1 and Chapter 2 studies. The authors chose an angle of 45\(^\circ\) because it was expected to be the most sensitive to the changes in the bypass flow percentage due to its larger DSR magnitude when compared to guide walls of lesser angles (as shown in Chapter 1 and Chapter 2).

### 3.4 Experimental Results

Fig. 3.1 (\( d = 10 \text{ ft.} \)) and Fig. 3.2 (\( d = 20 \text{ ft.} \)) examine the effect of the bypass flow percentage, \( p \), on the UGZ Depth at multiple cross-sections along the x-axis of the model. The x-axis location of each cross-section was defined by \( x = nL \), where \( n \) is equal to 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 (refer to Fig. 1.2 for the axis orientation).

Similar patterns exist for both guide wall depths. At the most upstream cross-section, \( x = nL \) where \( n = 0.1 \), there was the greatest in absolute value of the DSR along the full depth of the guide wall relative to cross-sections further downstream. At this location, the sweeping velocity at the guide wall had not built up a significant amount of momentum in the direction of the bypass. In addition, the changes in \( p \) present an unclear and varying signal in the UGZ Depth at this far upstream location.
Figure 3.1: A 3 x 3 plot showing the Upper Guidance Zone Depth, d*, as a function of the DSR threshold, t*, for a guide wall depth, d, of 10 ft. The nine plots each show a different “n” location along the x-axis of the model, where x = nL. Each plot consists of 8 different colored lines representing the different bypass flow percentages, p, from 1 to 15%.
Figure 3.2: A 3 x 3 plot showing the Upper Guidance Zone Depth, $d^*$, as a function of the DSR Threshold, $t^*$, for a guide wall depth, $d$, of 20 ft. The nine plots each show a different “n” location along the x-axis of the model, where $x = nL$. Each plot consists of 8 different colored lines representing the different bypass flow percentages, $p$, from 1 to 15%.
At the next downstream cross-section, \( n = 0.2 \), the effect of the bypass flow percentage had begun to develop a clear and quantifiable signal. Like at the upstream cross-section, the minimum DSR values occur towards the bottom of the guide wall. However, the lines representing \( d^*(t^*) \) for each bypass flow percentage noticeably spread further apart at locations further downstream and closer to the bypass (from \( n = 0.2 \) to \( 0.9 \)). At \( n = 0.2 \) the marginal increase in \( t^* \) per unit \( p \) at \( d^* = 10 \) ft. for a guide wall depth, \( d \), of 20 ft. is equal to approximately 0.01. At \( n = 0.9 \), this value increases to approximately 0.07. Similarly, at a \( d^* \) of 20 ft. these values change to 0.02 and 0.13. This pattern was prevalent throughout the data set, and thus the effect of the bypass on the UGZ Depth increases both in locations closer to the bypass and deeper in the water column.

Figure 3.3: This 1 x 2 figure (on left, \( d = 10 \) ft; on right, \( d = 20 \) ft.) shows the Upper Guidance Zone Depth, \( d^*(t^*) \), versus the “n” location along the x-axis of the model, where \( x = nL \). Sixteen lines representing combinations of the bypass flow percentage, \( p \), and the DSR Threshold, \( t^* \), are shown on each plot.
Fig. 3.3 (on left, d = 10 ft.; on right, d = 20 ft.) provides an alternate view of how $d^*(t^*)$ varies along the length and depth of the guide wall for a specified DSR Threshold, $t^*$, and bypass flow percentage, $p$. The two $t^*$ values used represent a low tier ($t^* = -1.0$) and high tier ($t^* = -0.33$) threshold introduced by Chapter 1. These thresholds determine the depth of the UGZ. At the low tier threshold, the downward velocity will be equal to the sweeping velocity in the worst case condition within the UGZ. At the high tier threshold, the downward velocity will be $1/3$ of the sweeping velocity in the worst case condition within the UGZ.

In Fig. 3.3, the change in $d^*(t^*)$ along the guide wall is clearly presented. At $n = 0.1$ the strong DSR is shown, similar to Fig. 3.1 & Fig. 3.2. Notably, $d^*(t^*)$ behaves similarly along the x-axis for both cases of $d = 10$ ft. and 20 ft., except the greater guide wall depth results in a set of $d^*(t^*)$ values that were proportionally less than those produced by the shallower guide wall relative to the guide wall depth. For each, a sharp increase in $d^*(t^*)$ occurs upstream followed by a slightly positive gradient in the positive x-direction in and around the midpoint of the guide wall and then either another sharp increase in $d^*(t^*)$ (for high bypass flow percentages) or a slight to sharp decrease in $d^*(t^*)$ (for low to mid bypass flow percentages). These figures make evident the increased effect of the bypass flow percentage in proximity to the bypass, but also demonstrate its substantial impact along the majority of the guide wall.

3.5 Discussion & Conclusion

The hydraulic conditions along each guide wall configuration was shown to be effected by a change in the bypass flow percentage, not only near the bypass but also
along the majority of the length of the wall. This analysis leads the authors to believe that a fish approaching a guide wall may be more likely to pass underneath it either at the most upstream section or, for low bypass flow percentages, at the downstream section close to the bypass. For low bypass flow percentages, increasing the depth of the guide wall in the downstream section could possibly increase the effectiveness of the guide wall. This approach may also be needed at the upstream section, depending upon where the majority of fish (horizontally and vertically) approach the structure.

Prior work within Chapter 1 and Chapter 2 used the DSR values at a few select locations to inform their estimation of the UGZ Depth for guide walls set at a variety of depths and angles. As expected, the UGZ Depth varies depending upon the section of the wall being measured. Furthermore, each of these studies are limited to the analysis of an idealized power canal. Undoubtedly, site-specific information is required to fully understand how the ratio of downward to sweeping velocities will change both along the length and depth of a guide wall. Changes in the bypass configuration, power canal geometry and bathymetry (among others) all have the potential to impact the DSR. Nevertheless, the UGZ Depths reported in Chapter 1 are a reasonable representation of the average conditions along the guide wall for \( p = 5\% \) (difference of approximately 0.85 ft. for \( t^*=-1.0 \) and 0.10 ft. for \( t^*=-0.33 \) at each guide wall depth). Therefore, the results presented in Chapter 1 should be considered as a general indicator of the UGZ Depth with the understanding that a more extreme DSR than expected may occur at the upstream and downstream ends of the guide wall. Future tests in situ with a variety of target species could be used to enhance these concepts and to increase the understanding of how each target species responds in the presence of a wide range of DSR values.
CONCLUSION

Guide walls offer a method to increase the passage efficiency of surface-oriented, out-migrating anadromous fish at a fishway. However, guide wall design parameters (e.g. wall depth and angle) and other site-specific information are likely to be very important factors determining guide wall performance. This dissertation examined the impact of guide wall design parameters on the hydraulic conditions upstream of a guide wall. In particular, the analysis focused on the ratio of the downward flow to the sweeping flow along the length and depth of the wall (referred to in each chapter as the DSR). Multiple methods were used, including CFD modeling and a physical, lab-scale model.

Chapter 1 and 2 demonstrated the effect of the guide wall depth and angle on the downward to sweeping velocity magnitude ratio. Lesser angles produced predominantly sweeping conditions, whereas greater angles produced large sections of downward dominant conditions. Increasing the guide wall depth resulted in a larger section of both sweeping conditions and downward dominant conditions. Increasing the guide wall depth also caused a greater downward velocity at the base of the wall.

Chapter 3 expanded on the work by calculating the impact of the bypass flow percentage in the developed CFD model on the Z-Velocity Ratio. Changes in the bypass flow percentage were shown to significantly effect this ratio of downward to sweeping flows, particularly in the area closer to the bypass, but did so along the majority of the guide wall. This chapter made it clear that future work is needed to characterize the flow field under a wide range of guide wall angles, depths, and bypass flow percentages.
Future work is necessary to refine guide wall design and operation, including 1) measuring the flow field under different approach velocities, bypass flow percentages, guide wall depths, and guide wall angles, 2) estimation of head loss and overall cost of the project, 3) determining the effect of vertical tilt of a floating guide wall on the metrics used in this study, and 4) testing in situ with the various fish species of interest to better understand their behavioral response to the structure.
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