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A computational fluid dynamics modeling study of guide walls for downstream fish passage

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ABSTRACT

A partial-depth, impermeable guidance structure (or guide wall) for downstream fish passage is typically constructed as a series of panels attached to a floating boom and anchored across a water body (e.g. river channel, reservoir, or power canal). The downstream terminus of the wall is generally located nearby to a fish bypass structure. 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). The goal of this study is to determine the combination of guide wall design parameters that will most likely increase the chance of surface-oriented fish being successfully guided to the bypass. To evaluate the flow field immediately upstream of a guide wall, a parameterized computational fluid dynamics 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° 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.

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1. 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 (McDowall, 1997). For instance, anadromous clupeids (genus *Alosa*) are born in a freshwater 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 (Weiss-Glanz et al., 1986). In addition, potamodromous fish perform migrations for the purposes of both feeding and spawning, but only within freshwater 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. Despite substantial efforts, issues related to passage of fish both up and downstream of dams are not yet fully resolved (Bunt et al., 2012; Enders et al., 2009). 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.

At a typical hydropower facility there are three primary routes of downstream passage. 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 typically constructed in close proximity to the turbine intakes to reduce the number of fish passing through the turbines. The chal-

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Notation

d	Guide wall depth (ft.)
$d^*(t^*)$	Upper Guidance Zone depth (ft.)
DSR	Downward to sweeping velocity ratio (−)
$DSR_{\min}$	Minimum downward to sweeping velocity ratio at each cross-section (−)
H	Water depth (ft.)
ℓ	Approach distance (ft.)
L	Distance along the x-axis from the upstream to downstream ends of the guide wall (ft.)
MMR	Maximum to mean velocity ratio (−)
p	Percent of the flow through the bypass relative to the flow through the model inlet (%)
Q_B	Total flow rate into bypass (ft^3/s)
Q_C	Total flow rate under guide wall (ft^3/s)
Q_T	Total flow rate through model inlet (ft^3/s)
t^*	Downward to sweeping velocity ratio threshold (−)
V	Average approach velocity (ft/s)
V_x	Mean velocity in the x-direction (ft/s)
V_y	Mean velocity in the y-direction (ft/s)
Vz	Mean velocity in the z-direction (ft/s)
W	Channel width (ft.)
θ	Angle of the guide wall relative to the side wall of the power canal (degrees)

lenge 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). Guidance technologies (e.g., louvers, racks, screens, perforate plates, guide walls) are designed for this purpose.

Like other fish passage devices, guidance technologies rely on the rheotactic response of fish (among other factors) to improve downstream passage efficiency and reduce migration delay (Schilt, 2007). 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° 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 an angle of 45° or less to the flow field, thus creating a hydraulic cue designed to elicit a negative rheotactic response from migrating fish. This cue encourages their movement downstream towards the bypass.

In the case of a partial-depth guide wall (Fig. 1) that is aimed at guiding surface-oriented fish, 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. NextEra Energy Maine Operating Services, LLC, (2010), Kock et al. (2012), and Faber et al. (2011) showed instances where a large proportion of downstream migrating fish passed below a guide wall, possibly due to a strong vertical velocity component.

A guide wall 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). The concept of a floating guide wall may have originated after dam operators observed fish accumulating along debris booms, similar to the booms used for a floating guide wall.

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. This analysis is performed through sophisticated numerical modeling referred to as computational fluid dynamics (CFD).

2. Methodology

To evaluate the flow field immediately upstream of a guide wall, we used a parameterized CFD model of an idealized power canal (© ANSYS Fluent v 14.5, 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 is reached. Section 2.1 describes the model domain (or geometry of the model). Section 2.2 introduces the pertinent design parameters and details the range and interval over which each is examined. Section 2.3 defines each of the boundary conditions applied to the model. These are the numerical conditions applied to the perimeter edges and faces of the model domain and must be satisfied within the solution. Section 2.4 describes the mesh of the CFD model. This pertains to the methods used to divide (or discretize) the region within the model domain into a large number of small finite control volumes. Section 2.5 details the solvers (or numerical solution scheme) used to calculate the model results and the convergence criteria applied to the solvers.

2.1. Model domain

Fig. 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 was fixed and the approach distance ℓ was held constant at 25 ft.(7.62 m). The longitudinal length of the guide wall, L, varies according to the angle of the guidance structure, θ. The canal width, W, was 100 ft. (30.48 m) and the canal depth, H, was 40 ft. (12.192 m). The width of the bypass was 0.1 W or 10 ft. (3.048 m) The depth of the bypass opening was 0.25H or 10 ft. (3.048 m). The total flow through the model inlet, Q_T, the flow through the bypass outlet, Q_B, and the flow through