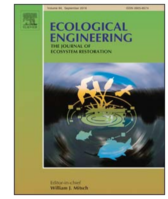
Ecological Engineering 115 (2018) 122–138

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



# Downstream fish passage guide walls: A hydraulic scale model analysis

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ARTICLE INFO

*Keywords:*
Fish passage
Hydraulic models
Velocity measurements
Guide walls
Downstream

ABSTRACT

Partial-depth guide walls are used to improve passage efficiency and reduce the delay of out-migrating anadromous fish species by guiding fish to a bypass route (i.e. weir, pipe, sluice gate) that circumvents the turbine intakes, where survival is usually lower. Evaluation and monitoring studies, however, indicate a high propensity for some fish to pass underneath, rather than along, the guide walls, compromising their effectiveness. In the present study we evaluated a range of guide wall structures to identify where/if the flow field shifts from sweeping (i.e. flow direction primarily along the wall and towards the bypass) to downward-dominant. Many migratory fish species, particularly juveniles, are known to drift with the flow and/or exhibit rheotactic behaviour during their migration. When these behaviours are present, fish follow the path of the flow field. Hence, maintaining a strong sweeping velocity in relation to the downward velocity along a guide wall is essential to successful fish guidance. Nine experiments were conducted to measure the three-dimensional velocity components upstream of a scale model guide wall set at a wide range of depths and angles to flow. Results demonstrated how each guide wall configuration affected the three-dimensional velocity components, and hence the downward and sweeping velocity, along the full length of the guide wall. In general, the velocities produced in the scale model were sweeping dominant near the water surface and either downward dominant or close to the transitional depth near the bottom of the guide wall. The primary exception to this shift from sweeping do downward flow was for the minimum guide wall angle tested in this study (15°). At 15° the flow pattern was fully sweeping dominant for every cross-section, indicating that a guide wall with a relatively small angle may be more likely to produce conditions favorable to efficient guidance. A critical next step is to evaluate the behaviour of migratory fish as they approach and swim along a guide wall in a controlled laboratory environment.

## 1. Introduction

Guide walls are a device similar to bar racks, screens, louvers, and perforated plates that are implemented to improve downstream fish passage at hydroelectric facilities (Schilt, 2007). Guide walls are generally designed as steel panels that are suspended down from the water surface by a floating boom (Scott, 2012). The downstream end of the guide wall is typically fixed alongside the bypass opening (i.e. safe passage route), whereas the upstream end of the guide wall may be fixed to a power canal wall or anchored within the river channel. Out-migrating fish are expected to approach the partial-depth, angled wall and be actively guided to the downstream bypass opening. The target species for these structures include a wide range of surface-oriented anadromous and potadromous fish at various life stages, although juvenile salmonid and alosine species are most common.

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 enters is the “Approach Zone”, located about 100–10,000 m 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. Fish movement typically includes both actively swimming and passively drifting. Next is the “Discovery Zone”, located about 10–100 m 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. Last is the “Decision Zone”, located about 1–10 m from the dam. Key features here that impact fish behavior are velocity, acceleration, turbulence, sound, light, structures, other fish (Larinier, 1998). Within this zone, the turbine intakes create a strong downward flow field. The purpose of the guide wall is to alter the flow in the “Decision Zone”, and partially the “Discovery Zone”,

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https://doi.org/10.1016/j.ecoleng.2018.02.006
Received 22 March 2017; Received in revised form 18 January 2018; Accepted 8 February 2018
0925-8574/ Published by Elsevier B.V.

**Notation**

| | |
|---|---|
| F | Froude number (−) |
| R | Reynolds number (−) |
| W | Channel width (m) |
| H | Water depth (m) |
| $Q_T$ | Total flow rate into flume ($m^3\,s^{-1}$) |
| $Q_B$ | Total flow rate into bypass reservoir ($m^3\,s^{-1}$) |
| $Q_C$ | Total flow rate under guide wall ($m^3\,s^{-1}$) |
| $L$ | Distance along the x-axis from the upstream to downstream ends of the guide wall |
| $DSR$ | Downward to sweeping velocity ratio (−) |
| $DSR_{min}$ | Minimum downward to sweeping velocity ratio at each cross-section (−) |
| $V_{mean}$ | Mean of the velocity magnitude above the bottom of the guide wall at each cross-section ($m\,s^{-1}$) |
| $V_{max}$ | Maximum velocity magnitude above the bottom of the guide wall at each cross-section ($m\,s^{-1}$) |
| $V_x$ | Mean velocity in the x-direction over the 60 s data collection period for each data point |
| $V_y$ | Mean velocity in the y-direction over the 60 s data collection period for each data point |
| $V_z$ | Mean velocity in the z-direction over the 60 s data collection period for each data point |
| $d_P$ | Prototype guide wall depth (m) |
| $d_L$ | Laboratory guide wall depth (cm) |
| $d_{P^*}$ | Upper guidance zone depth for the prototype (m) |
| $t^*$ | Downward to sweeping velocity ratio threshold |

such that adult and particularly juvenile surface-oriented anadromous fish are actively guided to a downstream surface bypass or collection system.

Although guide walls are intended to actively guide fish to a safe passage route, some fish pass under, rather than along, the guide wall and subsequently pass through turbine intakes where survival is often low. Monitoring studies have shown juveniles, in particular, can have a high propensity to pass underneath the guide wall rather than be guided to the bypass (NextEra Energy Maine Operating Services, LLC, 2010; Faber et al., 2011; Kock et al., 2012). This failure to effectively guide out-migrating fish to the bypass may result from poor design and placement of the wall. Many migratory fish species, particularly juveniles, are known to drift with and/or swim in the same direction as the flow field during their migration. Consequently, a weak sweeping velocity (i.e. water velocity parallel to the guide wall directed towards the bypass) combined with a strong downward vertical velocity is likely to reduce guidance efficiency by directing and/or transporting fish below the wall. The goal of the present study is to identify where/if the flow field shifts from sweeping to downward-dominant along the full length of a guide wall set at a wide range of guide wall depths and angles to flow.

Mulligan et al. (2017) studied the effect of the primary design parameters of a partial-depth guide wall (i.e. angle to approach flow and depth) on the flow pattern around the wall and the velocity magnitudes that a fish may encounter. The analysis was based on a computational fluid dynamics (CFD) model built in ANSYS ® Fluent V. 14.5. Model outputs included three-dimensional velocity components that were thought to affect fish movement along the wall. The velocity components of interest were the sweeping velocity and the vertical velocity. The main findings of Mulligan et al. (2017) demonstrated the depth to which sweeping velocities were greater than the downward vertical velocities under a wide range of guide wall depths and angles at the longitudinal midpoint of the wall. The authors suggested that this information could be used to inform the design of a partial-depth guide wall given the expected swimming depth distribution of the target fish species. The authors theorize that a guide wall designed to create sweeping dominant conditions within the water column range of the out-migrating target fish species would likely increase the overall effectiveness of the guide wall.

Ineffective guidance may result from several different modes of failure. First, a lack of attraction flow into the bypass relative to the total flow in the main channel. Typically, between only 1% and 17% of the mean annual river flow is discharged through the bypass route (Johnson and Dauble, 2006). An increase in the bypass flow percentage could result in an increase in guidance efficiency, although it would cause a reduction in power generation. Second, the flow pattern that develops around an impermeable guide wall (a function of the bypass flow percentage and the guide wall depth/angle) may contain a downward vertical velocity that exceeds the sweeping velocity. In these instances, fish may be exhibiting rheotactic behavior (Montgomery et al., 1997) and following the flow field below the guide wall. Third, the fish may become fatigued to the point of entrainment if attempting to swim against the flow field or be physically unable to swim against the encountered velocities for any length of time and be swept below the guide wall. Fourth, the approaching fish may be swimming deeper than expected, allowing them to easily swim below a guide wall that was intended for surface-oriented fish species. Lastly, the fish may be responding to some other environmental stimuli such as turbulence, velocity gradients, acceleration (Enders et al., 2012), sound (Fay and Popper, 1999; Kynard and O'Leary, 1990; Taft et al., 2001), and light (Wickham, 1973).

The main contributions of the present study are the water velocity profiles of the flow field along the full length of the guide wall for a variety of guide wall configurations. The water velocity profiles indicate where the flow shifts from sweeping to downward-dominant along a guide wall and illustrate where/if the velocity magnitude may overcome the swimming capability of the target fish species. This markedly expands upon the authors' previous work which used CFD models to examine the flow field but only studied conditions at the longitudinal mid-point of the guide wall. To the authors' knowledge, there are no comparable studies on guide walls other than those presented here and in our previously published CFD paper. This new information adds to the sparse literature on this subject, leads to further questions about the effectiveness of a guide wall, and points to the need for more evaluation studies of fish swimming along these structures.

## 2. Experimental design

### 2.1. Scale model design

The laboratory model was 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 illustrates the laboratory setting and Fig. 2 provides the plan view of the scale model. Note the x-y-z-axis orientation in Fig. 2 for later reference. Emphasis was placed on the scale 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 were the Froude number (a ratio of the inertial force to the gravitational force, F) and the Reynolds number (a ratio of the inertial force to the viscous force, R). The scale model and the prototype possessed identical Froude numbers, although they varied in Reynolds number. Acknowledging this limitation, the goal was to ensure that turbulent flow ($R > 10^4$) existed in all scale model versions.

Table 1 details each scale model configuration and the associated prototype model. Other pertinent fixed parameter values are shown in Fig. 2 and include W (channel width: 76.2 cm – laboratory, 15.2 m – prototype), H (water depth: 76.2 cm, 15.2 m), $Q_T$ (total flow rate into