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Research Paper

Pressure gradients in a steeppass fishway using a computational fluid dynamics model

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ABSTRACT

The Alaska steeppass is a fishway used commonly in the eastern United States and in remote locations, and is an example of the many configurations of fishways, ladders, bypass channels and other structures intended to facilitate fish mobility in river systems fractured by in-stream structures. Passage success for this fishway is varied and depends on many factors including species of interest. The cause of this variation is relatively unknown and typically ascribed to "other hydraulic factors", meaning a hydraulic variable other than the mean (spatial and temporal) velocity. Attempts have been made to move from velocity-based to energy-based fish passage models to pinpoint these "other factors", however energy-based passage models rely on assumptions that may be inappropriate when applied to hydraulically complicated fishways. An assumption that has facilitated wide ranging discussions of the performance of fish ladders without the develop of very specific and detailed computational models is that pressure forces that a fish might experience can be adequately estimated using uniform flow pressure distributions. In uniform flow, the vertical pressure distribution is as if hydrostatic, and there is no pressure gradient in the horizontal plane. To test this assumption, very detailed three-dimensional hydraulics information was generated from a computational fluid dynamics (CFD) model of the steeppass to calculate the pressure. The results demonstrate the significance of considering dynamic pressure distributions when modeling the interaction between hydraulics and fish mobility.

1. Introduction

Engineers and ecologists work together to design fish passage structures that accommodate a desirable level of fish mobility under the constraints of the hydraulic and hydrologic setting. Designs of fish passage structures are often based on guidelines developed from observation. As fishways are expected to pass a wider range of target species at higher rates these guidelines can be insufficient. A mechanistic approach was introduced by Behlke (1987, 1991), Behlke et al. (1993) to use the concepts of fish power and energy expenditure to evaluate fish negotiating passage structures. This method proposes that by summing the hydraulic forces acting on a swimming fish the propulsive force can be estimated and by extension to a particular hydraulic challenge the energy and power requirements can be calculated. Estimates of energy required to pass a particular hydraulic challenge could be compared to observed power capabilities and energetic data for fish that have successfully passed structures to determine if the challenge is reasonable for a particular species. This method has gained very little traction in fish passage design but could be used to compare the energy required for fish to pass different structures or negotiate different swim pathways in a single structure. Behlke acknowledged that one-dimensional and steady analyses formed the framework for his approach which was specific to culverts. Fish passage researchers have applied Behlke's ideas to include other structures and the influence of three-dimensional flow using numerical models. Access to CFD model predictions of fishway hydrodynamics opens the door to making more comprehensive energy estimates as shown by Khan (2006), Blank (2008) and Plymesser (2014). These three studies relied heavily on uniform flow pressure distributions to estimate the forces that influence energetic expenditure. The objective of this study is to investigate the magnitude and patterns of the pressure gradients that may be expected in a steeppass fishway.

2. The steeppass fishway

Fishways are structural amendments that ameliorate problems presented by in-stream barriers that reduce fish mobility. The Alaska steeppass fishway is used extensively on coastal streams, originally developed by Ziemer (1962) for use at sites that were difficult to access with construction equipment and materials. The Alaska steeppass uses a

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series of symmetric, closely spaced baffles to dissipate energy and reduce water velocities in the chute. The steeppass was originally designed to provide upstream passage for salmon in Alaska; however it has also been used to pass non-salmonid species in locations outside Alaska (Haro et al., 1999).

The Steeppass fishway was studied by Ziemer (1962), Rajaratnam and Katopodis (1991), and Odeh (1993) using full-scale physical models to explore one-dimensional water velocities, flow rates and water surface profiles. Results of all three of these one-dimensional physical studies are comparable and indicated that the Steeppass fishway is an efficient energy dissipater, particularly so at steep slopes, as evidenced by the water velocities measured in the fishway. The bulk water velocity ranges from 0.46 to 1.07 m/s over the typical operating range of inlet heads (Ziemer, 1962; Odeh, 1993). Another approach to the study of steeppass hydraulics was to measure velocities on a closely spaced three-dimensional grid throughout the structure to characterize flow patterns (Wada et al., 2000).

3. The computational fluid dynamics (CFD) model

The authors used commercial software to develop a computational model of a deepened A40 steeppass (“A” or “C” specifies nuances of the fishway geometry, “40” specifies that the fishway wall height is 40 inches, rather than the 27 inch standard “A”). Flow 3D software (Flow Science, 2012) uses a finite-volume, transient solution to the Reynolds-averaged Navier-Stokes equations. The general CFD process and implementations specific to modeling the Model A40 steeppass are detailed in Plymesser (2014). The simulated steeppass fishway had an upstream inlet depth of 91.4 cm and a nominal downstream slope of 1:8 (vertical to horizontal) and the baffles are spaced 25.4 cm. In summary:

- a volume-of-fluid method was used to define the fluid surface (Hirt and Nichols, 1981) and the fluid surface was located a sufficient distance beneath the upper boundary to the domain that it did not interact with the boundary,
- a two-equation turbulence model was selected to adequately describe the turbulent length and time scales, with renormalization-group methods (Yakhot and Smith, 1992) and transport equations similar to the standard k-ε model (the RNG model generally has wider applicability than the k-ε model as the constants that are found empirically for the k-ε model are derived explicitly in the RNG model),
- the computational domain was divided into a 7.62 mm mesh of fixed hexahedral cells with solutions progressing in space and time and with the solid model of the fishway located within the computational domain,
- the size of the cells required was small to resolve the flow field near the ends of the thin baffles,
- the air entrainment routine in Flow3D was not implemented, the required calibration information for the specific model was not available,
- the boundary conditions on the inlet and outlet to the domain were pressure boundaries with prescribed water surface elevations,
- the bottom and sides of the domain were defined as no-slip wall boundaries and the upper surface of the computational domain was a symmetry boundary,
- the model was initiated with static water filling the interior of the model that was not occupied by the solid fishway, with a water surface connecting the prescribed inlet and outlet water levels,
- the solid components of the steeppass were assigned a roughness height of zero, appropriate because the form roughness of the baffles dominates and the influence of the roughness height of the aluminum plate is minimal in comparison.

The CFD model output was compared to measurements from the full-scale physical model at the S.O. Conte Anadromous Fish Branch (Plymesser, 2014). The water surface profile is a CFD model-generated outcome and was compared to observed values. The RMSD between the observed and predicted water surfaces was 37 mm (-3.3% percent error) for the simulation discussed herein. In three other configurations of fishway slope and inlet head level not detailed herein, the CFD model predicted the observed water surface profile with between −0.6% and −5.9% error. Over all four comparisons, the model consistently predicted the observed water surface elevation including the steady undulations and shape of the profile. The average error between modeled and observed water surface elevations was on the order of the height of the dynamic waves observed on the water surface. The CFD model output was also compared to standard rating curves for the steeppass fishway (Odeh, 1993). The volumetric flow rate is a CFD model generated output in the framework of the boundary conditions used. For the simulation discussed herein, the CFD generated flowrate differed from the rating curve flow rate by 7.2%. Over all four hydraulic combinations, the difference was 7%. Two three-dimensional mesh size simulations were performed on the hydraulic combination having low inlet head and shallow slope to ascertain the adequacy of the spatial resolution. The coarse mesh had 9.14 mm cells and a slightly thicker baffle thickness (reducing the need for clarity at the sharp edges of the baffle) and the fine grid had 7.62 mm cells and a thinner baffle thickness. The structured mesh model that was used required a fine mesh size to accommodate thin, angle baffles in the steeppass fishway. Any cell size less than 7.62 mm resulted in a model that exceeded the computational facilities available at the time. The two approaches resulted in water surface profiles within 0.4% of each other. Because the coarse and fine meshes predicted similar water surface profiles for this hydraulic configuration, no further refinements were made and the coarse mesh was used for all simulations. All simulations were carried out until the final 10 s of model time had less than 0.1% variation in volume of fluid. All simulations required 20–30 s of model time to achieve stationarity.

4. Theory and computations

The two-dimensional vector representation of Fig. 1 shows the force balance on a particle (or a relatively small volume such as a differential element) as it passes through a moving flow field. Forces identified on the differential scale can be integrated over the body or surface of the fish to arrive at the magnitude and direction of the forces that impact energetics. The nature of CFD output, closely spaced results on a three-dimensional grid, provides an effective framework for studying the force balance. This process is confounded by the presence of the swimming fish which impacts the flow field. Recent advances in CFD modeling have included numerical studies of the interaction between fluid flow and fish locomotion (Ren et al., 2016). In the current project, the CFD model was of the flow field in the fishway and did not include a model of the fish.

The steeppass geometry generates a complex flow field (e.g. velocities, pressures, forces) that appears statistically steady but is actually very diverse in space, and at any point in space is unsteady in time. The contributions to the force balance on the small volume shown in Fig. 1 are the weight ($\mathbf{W}$), the net pressure force ($\mathbf{F}_P$), the net viscous or shear force ($\mathbf{F}_S$), and the mass force ($\mathbf{F}_M$). All these forces may have components in each of the three cardinal directions (the components in the y-direction are not shown).

The resultant viscous or shear force, $\mathbf{F}_S$, can be calculated by integrating the shear stress over the area of the object. The mass force, $\mathbf{F}_M$, is the result of the object accelerating (or decelerating) according to Newton’s second law and can include the fluid near the object (Webb, 1975) due to the no-slip condition between the object and the fluid (virtual mass). In some settings, the Basset-Boussinesq force that describes the effect of the temporal delay in the development of the boundary layer of an accelerating object is added to the mass force.

The net vertical pressure force ($\mathbf{F}_{Pz}$) is often referred to as the