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Journal of Hydro-environment Research 12 (2016) 119–129

Journal of Hydro-environment Research

www.elsevier.com/locate/jher

Research papers

Three-dimensional simulation and experimental study for optimising a vertical slot fishway

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Received 9 February 2015; revised 9 May 2016; accepted 23 May 2016

Abstract

Vertical slot fishways are structures that facilitate energy dissipation using a specific pool, slot and baffle design; these structures are common in West China. To develop an effective and simple design, the flow patterns in the pools must be fish-friendly. To assist in design optimisation, a three-dimensional (3D) computational fluid dynamics (CFD) model and an experimental study for validating the model using an equivalent scale physical model were conducted. This paper presents the results for detailed hydraulic structures, including velocity fields, flow patterns, recirculating flows and turbulent structures in a pool, for conditions with slopes of 4.2% and 2.6% and a new structure with a long 'L'-shaped baffle. The new structure can effectively improve the flow patterns of fish by adopting a burst-coast mode. The mainstream velocity decreases from 1.22 m/s to 0.85 m/s, and the average proportion for the recirculation region decreases from 30.16% to 21.73% compared with the same slope and creates a 'Ω'-shaped flow pattern. The results provide insight of the flow patterns in vertical slot fishways, which can be used to guide future designs.

Keywords: Vertical slot fishway; Volume of fluid model; Hydraulic structures; Free surface

1. Introduction

Fishways are hydraulic structures that enable fish to overcome obstructions, such as dams and sluices, to spawning and migration. The design of fishways requires hydraulic, ecological, economical and engineering considerations. Vertical slot fishways are common as they enable variations in discharge and permit fish to ascend fishways at any depth. Fishways facilitate energy dissipation by specific pool, slot and baffle designs. The flow patterns in pools are important for guiding fish through the pools. The velocity and water depth, as well as the turbulence level and eddy size, significantly affect the swimming cost of fish.

The earliest vertical slot fishway was constructed at Hell's Gate Dam on the Fraser River in Canada (Clay, 1995). This fishway became the most commonly employed fish ladder in North America. Rajaratnam et al. conducted a series of systematic experiments of flow patterns. They investigated the mean flow structure in pools for seven different designs using models with four different scales (Rajaratnam et al., 1986) and examined 18 designs of vertical slot fishways that were already employed in the United States (Bell, 1973) to develop an effective and simple design (Rajaratnam et al., 1992), of which designs 6, 16, 18 were recommended for practical use. Based on their study, Wu et al. (1999) analysed the structure of the mean flow of design 18 for three different slopes: 5%, 10%, and 20%. Puertas et al. (2004) measured the mean flow structure of designs 6 and 16 for two different slopes using mirco-acoustic Doppler velocimetry. Both of the studies confirmed the linear relation between the dimensionless discharge and the relative flow depth for each design. An experimental study for mean and turbulence structures of the flow in the pools for Design 18 (Liu et al., 2006) was conducted. The measurement results provide insight of the flow patterns in vertical slot fishways.

The CFD model also provides an effective method for quantitatively analysing hydraulic structures. The use of a three-dimensional simulation model for simulating the hydraulics is a recent development. Meselhe and Odgaard (1998) have reported a 3D CFD model of a 1:16 scale physical model of the

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http://dx.doi.org/10.1016/j.jher.2016.05.005

1570-6443/

Wanapum Dam in the Columbia River in Washington. The combined use of a CFD model, a physical model, and a kinematic flow model has been reported by Muste et al. (2001) for analysing forebay hydraulics. The numerical fish surrogate model (Goodwin et al., 2004) was developed to provide necessary fish passage information. The 3D hydrodynamic simulation of flows for fishways at the Dalles Dam was conducted by Li et al. (2006). The CFD model can be employed to improve the design of intake for better hydraulic performance in attracting fish.

Based on the experimental results, the ratio of length to width from 1.2–1.5 should be considered as the proper setup due to effective energy dissipation. Despite the advantage of reliability and intuition for the physical model experiment, the challenges of cost and modification remain. The 3D CFD model that can be validated by experiment provides another reliable method for improving the success rate of fish migration, whereas the engineering, ecological and fish-friendly considerations require a more detailed analysis. Considering the complexity of the flow, head drop and jet mixing, a CFD model that can successfully address free surfaces and coupled with a k-ε turbulence model was selected for application. The results of this study are presented in this paper with the hope that they will facilitate design and create more ecologically friendly flow structures in vertical slot fishways.

2. CFD model and simulation

2.1. CFD model

The numerical model is based on the volume of fluid (VOF) model theory. The VOF model solves the momentum equations and tracks the volume fraction of fluid and atmosphere throughout the free-surface interface domain. Coupled with a three-dimensional k-ε turbulence model, the numerical model is applied to predict the flow field, which can also simulate the fluctuation of the water surface by energy dissipation through the vertical slot (Hirt and Nichols, 1981).

The tracking of the interface between the water and the air is accomplished by the solution of a continuity equation for the volume fraction, which has the following form:

$$\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = 0 \tag{1}$$

where α_q is the volume fraction for phase air, $\alpha_q = 1$: above the water surface, $\alpha_q = 0$: in water and u_i is the velocity for phase i. The equation cannot be solved for primary phase water, which will be solved based on the equation $\alpha_p + \alpha_q = 1$ and by implicit time discretisation.

$$\frac{\alpha_q^{n+1} - \alpha_q^n}{\Delta t} V + \sum_f \left(U_f^{n+1} \alpha_{q,f}^{n+1} \right) = 0 \tag{2}$$

where $n + 1$ is the current time step-indicating index, V is the volume of the cell, U_f is the volume flux through the face based on normal velocity, and α_{qf} is the face value of the phase q volume fraction computed from the second-order upwind scheme.

The momentum equation is solved throughout the entire domain, and the velocity field is shared for both water and air, which has the following form:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} - \rho g + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \tag{3}$$

where ρ is the water density of 998.5 kg/m^3, P is the pressure, μ is the dynamic viscosity, and μ_t is the turbulent viscosity related to the kinetic energy k and its dissipation rate ε, which is expressed by the following equations

$$\mu_t = C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = G_k - \rho\varepsilon + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \tag{5}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{C_{1\varepsilon}\varepsilon}{k} G_k - C_{2\varepsilon}\rho \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \tag{6}$$

where G_k is the generation of turbulence kinetic energy due to the mean velocity gradients, which is calculated as follows:

$$G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}. \tag{7}$$

The constants $C_\mu = 0.09$, $C_{1\varepsilon} = 1.44$, and $C_{2\varepsilon} = 1.92$, and the turbulent Prandtl numbers for k and ε were also given, respectively, as $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$.

2.2. Computational domain

According to the body size of the fish, the length, width and slot width of each pool is 2.4 m, 2.0 m and 0.3 m; these pools are commonly employed in the Dadu River in China. The fishway has different slopes of 2.6% and 4.2%, and the slot formed by the fishway walls and baffles are vertical. For the first design T1, the slopes are 4.2% and 2.6%. The second design T2 has different slopes but the same slot width. The slot angle of 45°and the pool size are numerically evaluated, as shown in Fig. 1(a). Fig. 1(b) shows a different structure for the long ‘L’-shaped baffle, which is also employed for reducing the velocity near the slot. The computational domain includes the inlet, the outlet of the fishway, and nine pools, including two resting pools at both ends, as shown in Fig. 2.

2.3. Computational setting

The mesh of the model consists of 116,128 grid points for T1, 114240 grid points for T2 and 96304 grid points for T3 with a structured grid and Green–Gauss cell, which the grid convergence has been tested The mesh of T1 is a regular hexahedron with a minimum length 0.045 m, a maximum length of 0.133 m, and an average length of 0.089 m.

The mesh of T2 is a regular hexahedron with a minimum length of 0.053 m, a maximum length of 0.128 m, and an